EFFECTIVE APPLICATION OF SERVICE CORE IN A REINFORCED CONCRETE TALL BUILDING

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By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved:

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Lim Wei Fa

ABSTRACT

In response to the increasing demand by commercial activities, the construction of skyscrapers in city centre has increased tremendously. Malaysia, particularly in Kuala Lumpur has seen the construction of many new skyscrapers. In the structural design of tall buildings, simple concepts were normally adopted by engineers in the past to estimate the live loads. Although Malaysia is located strategically away from extreme condition in terms of violent wind flow or typhoon prone area, wind flow has gained significant attention by engineers to draw more accurate analysis in the structural design. In this research, the effect of different orientations of service core in a reinforced concrete tower with approximate height of 200 meters will be studied based on a case study (mix-development office tower) located in Kuala Lumpur. Wind loading on the case study will be based on The British Standard BS 6399 Loading for Buildings, Part 2. This paper provides an outline of conducting the analysis and illustrates the behavior of high-rise structures including lateral stiffness, dynamic response (period, acceleration) and human comfort criteria, in the context of the British Standard and National Building Code of Canada. Furthermore, the results of sensitivity analysis will be reviewed to achieve an optimum structure.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

The issue involved in the construction of tall buildings around the world is a response to the demand by commercial activities. It is also desirable that those commercial activities are to be as close to each other and to the city center as possible. Hence it is causing intense pressure on the availability of land space and high cost of land. Moreover it becomes a prestige symbol for corporate organizations in major city centers. The entire design team (architects, structural engineers and services engineers) would have to collaborate in the planning stage to agree on a form of structural system that would satisfy aesthetics value, safety and servicing requirements respectively.

1.1 Background of Study

Structural engineers need to take into account of wind and seismic load when designing tall buildings. When the tall buildings are subjected to lateral forces, it may be swaying too much thus causing human discomfort at higher level of buildings. It may also cause non-structural elements (façade, glasses, ceilings etc) to break. Hence a correct and suitable structural system is important in high rise structures to help resist shear and bending when the buildings are subjected to lateral forces generated by windy climates or earthquake.

There are two types of vertical load-resisting components in tall buildings. These include columns and walls. The latter will act either in an isolation manner or in assemblies as shear wall cores. Most tall buildings are now designed with perimeter structure consisting of closely spaced columns or widely spaced mega columns with braces and cores to contain and convey services including elevators, staircase and toilets. Together with the perimeter frame structure, the core structure may contribute to the stability of the tall buildings by acting as the principal load bearing element for both gravity and wind loadings.

1.1.1 Design Criteria

It is essential for the architects to satisfy the client's expectation concerning the aesthetics qualities of the building's exterior and also the needs of an intended occupancy, whether residential, commercial, or a combination of the two. Hence in most of tall buildings, the structural arrangement will be subservient to the architectural requirements of space arrangement and aesthetics. Therefore, the main design criteria are from the architectural point of view. Engineers are constrained within these criteria to fit the structural system into the established functional layout unless the structural requirements become a predominant factor in tall buildings. The vital structural criteria include the reserve of strength against failure, adequate lateral stiffness when building is subjected to lateral forces and dynamic comfort of the occupants.

1.2 Problem Statement

A compromise between conflicting demands of each respective design team (architects and engineers) to fulfill the requirements of function will be almost inevitable. Primarily, it is essential for the architect to satisfy the client's expectation concerning the aesthetic qualities and the internal functional requirements of the tall buildings. This also includes the orientation of service core being designed according to the architectural requirements. The constraint is, therefore, engineers have to develop a structural system satisfying the established design criteria efficiently and economically while fitting into the architectural layout. On the other hand, however, the service core approach in the structural element design is important in providing the stability for tall buildings subjected to wind load. The orientation of service core has also big impact in the stiffness and energy dissipation of tall buildings. Thus this will lead to a less-than-ideal structural solution that will tax the ingenuity and the patience of the structural engineer.

1.3 Objectives & Scope of Study

The purpose of this research is to study the significance of the different orientations of service core in Malaysia's tall buildings subjected to wind load. The objectives of this project are to study:

- The current practice of structural systems of tall buildings
- The significance of service core in tall buildings
- Significance of wind load on tall buildings in Malaysia
- Perception of motion criteria for tall buildings subjected to wind
- The behavior of tall buildings of different orientations of service core
- Optimum orientation of service core in tall buildings

Under the scope of study, a total of five cases of five different orientations of service core will be analyzed using ETABS. This will be based on a case study which is a proposed mix-development retail-office tower located in Kuala Lumpur. The effect of lateral load to the tower will be limited to wind load analysis because earthquake is not as significant as wind load in Malaysia. Hence the sensitivity analysis is only based on wind loaded structures, in the context of British Standard and National Building Code of Canada. More importantly, the study of the behavior of structural model for all cases will be emphasized in terms of lateral stiffness, dynamic response of the structures including along-wind and cross-wind acceleration and human comfort criteria. Moreover, all factors considered will be reviewed to achieve an optimum structure.

CHAPTER 2
LITERATURE REVIEW & THEORY

2.1 Structural System

The primary function of structural system of a building is to transfer all the loads acting on the building to the foundation. Thus it is expected that a structural system is designed to resist the vertical gravity loads (including dead and imposed loads) and the lateral wind and earthquake loads. According to Ho (2007), structural system will have great impact on the exterior aesthetics views of a buildings and the interior space planning.

Nair (2007) discussed that for low-rise and medium-rise structures, the basic principles of vertical and horizontal subsystem design remain the same. The analysis and design with respect to lateral load forces have only been checked using the vertical load-resistant system as long as it is able to resist lateral forces. For high-rise buildings, however, it is another case. The vertical subsystems might not able to resist the lateral forces. If the vertical subsystems might able to resist lateral forces but the structural cost may increase tremendously. This is because the quantity of materials required for resisting lateral loads increases.

Again, Nail (2007) mentioned that larger columns or wall sections at lower floor in a tall building are required to support the accumulated gravity load from stories above. In addition, the same column or wall sections need to resist lateral forces at the same time.

A skeleton of a skyscraper can be visualized as a beam cantilevering from the earth. This tall building must therefore have adequate structural system to resist shear force as well as bending. It is because the laterally directed force such as wind tends to snap (shear) the building and topple it (bending). Ali and Moon (2007) presented in their paper mentioning that based on Fazlur Khan's argument, as the buildings' height increase beyond 10 stories, the stiffness rather than strength becomes the dominant factor in the design of structural system. At this point, the lateral drift starts controlling the design, thus the lateral load resisting system becomes important.

Fazlur Khan classified structural systems for tall buildings relative to their height in 1969. In the year of 1972 and 1973, Khan modified his "Heights for Structural System" diagram for both steel and concrete (see Khan and Rankine 1980, Ali 2001, and Ali and Moon 2007, as example). Figure 2.1 shows the classification of concrete structural system for office towers by Fazlur Khan.

Figure 2.1 Classification of concrete structural system for office towers

Structural systems of tall buildings can be divided into two categories which are interior and exterior structures. When the major part of the lateral load resisting system is located within the interior of the buildings, the system is interior structure. On the other hand, when the major part of the lateral load resisting system is located at the perimeter of the buildings, the system is exterior structure (see Ali and Moon 2007, as example).

In general, there are a few commonly used structural systems for tall buildings. These structural systems include:

- Shear Wall-Frame Interaction System
- Shear Walled Buildings
- Moment-Resisting Frames (MFR)
- Outrigger Systems
- Single Framed Tube
- Tube-in-Tube System

Further discussion will focus on wall-frame structures in which the case study for this research is adopting this structural system.

2.1.1 Shear Wall – Frame Interaction System

The mechanics of a shear wall-frame interaction system was studied by Khan and Sbarounis (1964) in a "milestone" paper. This shear wall-frame interaction system gave rise of taller concrete buildings (Ali 2001). In Ali and Moon (2007) paper, the shear wall-frame interaction system is applicable for buildings up to about 40 to 70 stories. The horizontal interaction between the walls and frames in a wall-frame structure causes an increased lateral stiffness of the structure, reduced moments in the walls and in a uniform structure, an approximately uniform shear in the frame. The shear walls or braced bents are often parts of the elevator and service cores while the frames are arranged in plan, in conjunction with the walls, to support the floor system as shown in Figure 2.2.

When a wall-frame structure is loaded laterally, the combined systems interact with each other horizontally so that the different free deflected forms of the walls and the frames cause them to deflect in the same way through the rigid floor diaphragm (slabs).

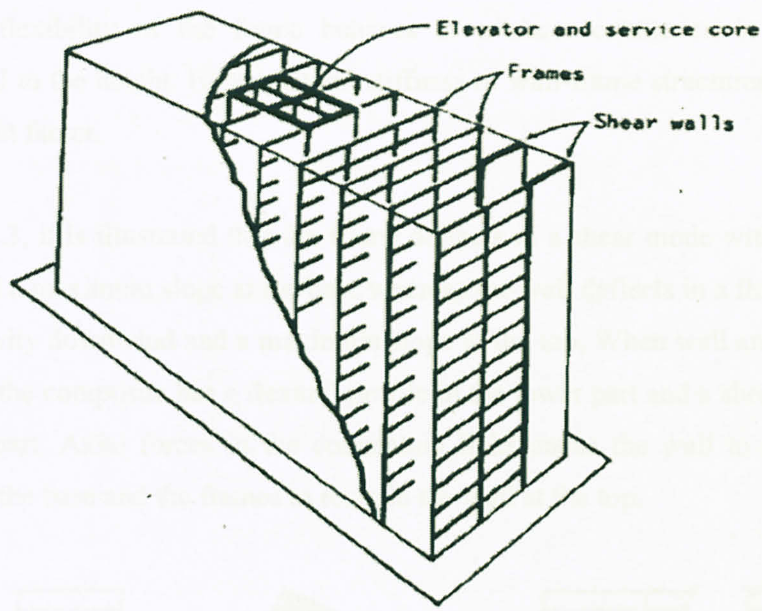


Figure 2.2 Illustration of wall frame structure

The interaction will be greater and the frame will be stiffer if building is taller with typically proportioned structures. On the whole, the lateral rigidity of the tall buildings increases. The advantages of a wall-frame structure depend on the amount of horizontal interaction, which is governed by the relative stiffness of the walls and frames, and the height of the structure. The following are the principal advantages for the horizontal interaction in designing wall-frame structures:

- The estimated drift may be significantly less than if the walls alone were considered to resist the horizontal loading

- The estimated bending moments in the walls or cores will be less than if they were considered to act alone

The higher the structure, the lesser the stiffness of the core compared to frame. At 50 stories or beyond than that, the separate horizontal stiffness at the top of a core would have reduced to being only one half as stiff as the frame. This reduction of top stiffness with the total height is due to the top flexibility of the core, which behaves as a flexural cantilever; it is directly proportional to the cube of the height. On the other hand, the flexibility of the frame behaves as a shear cantilever; it is directly proportional to the height. Hence, lateral stiffness of wall-frame structures is affected by the height factor.

In Figure 2.3, it is illustrated that the frame deflects in a shear mode with concavity upwind and a maximum slope at the base whereas the wall deflects in a flexural mode with concavity downwind and a maximum slope at the top. When wall and frame are connected, the composite has a flexural profile in the lower part and a shear profile in the upper part. Axial forces in the connecting links cause the wall to restrain the frame near the base and the frames to restrain the wall at the top.

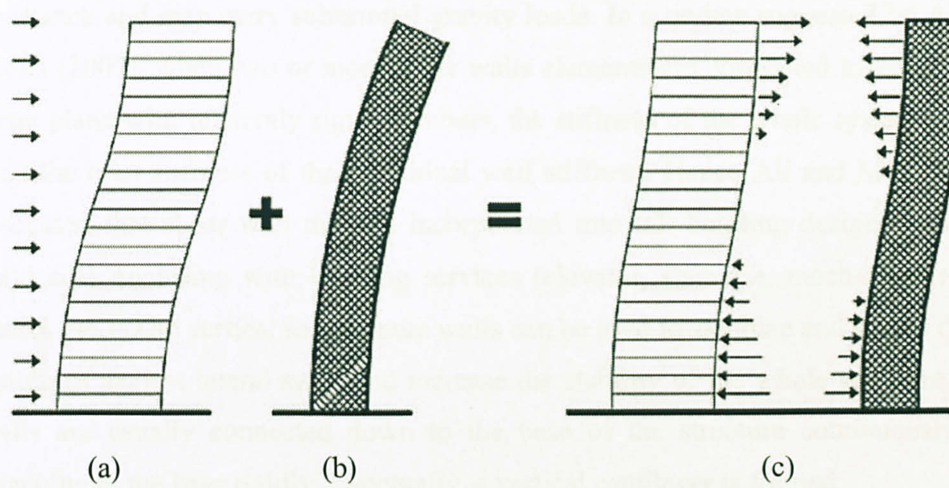


Figure 2.3 (a) Frame subjected to uniformly distributed horizontal load; (b) wall subjected to uniformly distributed horizontal load; (c) wall-frame structure subjected to horizontal load

The desirable effect of the wall-frame interaction is optimized to achieve significant reductions in the deflections and the wall moments. The system should be checked for drift. If the maximum total drift or storey drifts of walls and cores are exceeded, they should be stiffened by adjusting the lower region of the walls and cores.

2.2 Significance of Service Core in Tall Buildings

Building services in tall buildings enclosed by shear walls include lift shafts, lift lobbies, staircase, mechanical and electrical system, plant rooms and wash rooms. This is also known as service core in tall buildings. In fact, the core structure inside tall buildings may contribute to the stability of the structure by acting as the principal load bearing element for both gravity and wind loadings according to Ho (2007). This vertical core may resist lateral loads either in isolation manner or in conjunction with the perimeter structural elements when subjected to wind loads.

2.2.1 Core Walls Resist Lateral Load in Isolation Manner

For core walls resisting lateral load in isolation manner, for instance shear-walled building, lateral load is resisted entirely by shear walls alone. Walls that make up shear walls may be ranged from service core wall or walls surrounding staircase to free standing vertical walls. According to Nair (2007), shear wall provide lateral load resistance and may carry substantial gravity loads. In a review suggested by Ali and Moon (2007), when two or more shear walls elements are connected together in the same plane with relatively rigid members, the stiffness of the whole system is more than the total stiffness of the individual wall stiffness. Hence Ali and Moon (2007) discussed that shear wall may be incorporated into tall building design as vertical solid core enclosing with building services (elevator, staircase, mechanical rooms, shafts, etc.). The vertical service core walls can be used to stabilize and stiffen the tall buildings against lateral sway and increase the stability of the whole structure. Core walls are usually connected down to the base of the structure continuously thus attaching to the base rigidly. Eventually, a vertical cantilever is formed.

2.2.2 Core Walls Resist Lateral Load in Conjunction with Other Components

As for core walls resisting lateral load in conjunction with other structural elements (columns & beams), tube-in-tube system provides the centrally located core structure in tall buildings as part of the main lateral load resisting systems. The exterior closed spaced column spandrel beam grid (framed tube system) will form the outer tube. Likewise the inner tube is formed by the shear core walls. The shear resistant capacity of the inner core shear walls enhances the structural characteristics of the overturning resistant ability of exterior framed tube by reducing the shear deflection of the columns. Besides this, wall-frame system is also a combination of core walls and frame in resisting lateral load. Service cores are often part of shear walls while the frames are arranged in plan, in conjunction with walls to support the floor system. Section 2.1.1 has discussed the wall-frame system in details.

When wind load attacks on the façade, the load will be transferred to the core then is carried down to the foundations. The systems discussed in Section 2.2.1 and Section 2.2.2 have already shown that service core in tall buildings is significant in stiffening the structure and in resisting to lateral wind load.

It is also suggested by Ali and Moon (2007) that many possibilities exist with single or multiple cores in a tall building with regard to their location, shape, number, and arrangement. The location and arrangement of service core will be further studied in this paper.

Ho (2007) has discussed the structural system adopted for Asia Pacific tallest buildings in his paper. Table 2.1 shows the summary of his discussion.

Table 2.1 Structural System of Asia Pacific Tallest buildings

Buildings	Height (m)	Floors	Structural System
Taipei 101	509	101	Mega-columns are connected to **square-shaped core** with outriggers.
Petronas Towers	452	88	Reinforced concrete perimeter columns are tied with **reinforced concrete central core** by outrigger truss.
Jin Mao Tower	421	88	Composite mega-columns are linked with **octagon-shaped reinforced concrete core** by outrigger trusses.
International Finance Centre	415	88	Composite mega-columns are linked to **square-shaped reinforced concrete core** by outrigger trusses.
CITIC Plaza	391	80	Based on tube-in-tube system. Consisting reinforced concrete perimeter columns and **octagon-shaped reinforced concrete central core**.
Shun Hing Plaza	384	69	**Rectangular reinforced concrete central core** are connected to steel frame by outriggers.
Central Plaza	374	78	Based on tube-in-tube system. Consisting reinforced concrete perimeter columns and **triangular-shaped shear-wall core**.

From Table 2.1, the usage of service core as a structural system in tall buildings is significant. All the major tall buildings in Asia Pacific utilize mega-columns connected with core by outrigger system or the tube-in-tube system.

2.3 Wind Loading on Tall Buildings

Traditionally, simple concepts have been adopted in estimating live loads for structural design. Due to the increase of tall buildings concentrated in the city centre, wind load on high-rise structure has gained significant attention by engineers in carrying out more accurate structural analysis.

Wind flow may improve the air ventilation inside building, but it may also cause variety of problems, especially in tall buildings. The sway of some tall buildings extended into regions of high wind velocity may cause human discomfort. When the wind flow is in an extreme violent manner, the non-structural elements such as façade, windows, etc. may be damaged. Eventually it may fall down thus causing problems at the lower ground especially the safety of pedestrians. Hence it is particularly important to understand wind and its effect.

According to the paper of Mendis, et.al (2007), wind is a phenomenon of great complexity because of the many flow situations arising from the interaction of wind with structures. Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth's surface. These eddies give wind its gusty or turbulent character.

Structures, particularly those are tall or slender (flexible), respond dynamically to the effects of wind. The oscillations of buildings may interact with the aerodynamic forces to produce various kinds of instability including buffeting, vortex shedding, galloping and flutter. More importantly, in view of the comfort criteria for the occupants, the potential for disaster is so great that the design must be changed or the aerodynamic effects modified to ensure that this form of unstable behavior cannot occur.

Some particular human are surprisingly sensitive to vibration to the extent that motions may feel uncomfortable even if they correspond to relatively low levels of stress and strain. Therefore, serviceability considerations are utmost important in tall building design. Section 2.4 will further discuss the perception level of human to motion of tall buildings.

The structure's dynamic response is illustrated by Smith and Coull (1991) mentioning that the consideration for structure's response is only in the fundamental modes. This is because the exciting wind energy will generally be at frequencies much lower than the fundamental natural structural frequency. The higher modes (of smaller periods or higher frequencies) are insignificant because the amount of energy decreases with increasing frequency.

Furthermore, the response of tall building to wind action will be based on both along-wind and cross-wind motions. The former is due primarily to buffeting effects caused by turbulence whereas the latter is generally due to alternative-side vortex shedding. The cross-wind response may also be important with regard to the comfort of the occupants of the building. Figure 2.4 illustrates the dynamic response of structure to wind.

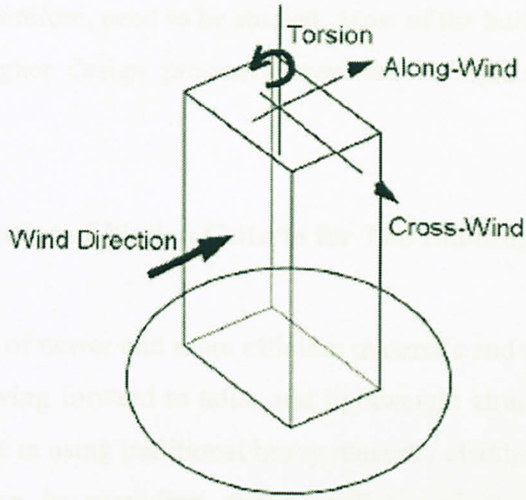


Figure 2.4 Wind response directions

2.3.1 Wind Condition in Malaysia

In Malaysia, there is no typhoon or extreme violent wind flow. Basically, the wind over the country is generally light and variable. According to the paper of Ismail, "Prospect of Wind-Driven Natural Ventilation in Tall Buildings", the mean wind speed in Malaysia is around the range of 1.5 m/s and 8 m/s and the direction of wind flow is variable. Hence, the mean surface wind is considered mild. However, as the height increases, the movement of airflow is eventually no longer influenced by the ground effect. The retarding effect due to the ground friction is slowly becomes almost zero or negligibly small. The variation of wind loads associated with turbulence change rapidly with height, say about 200 meters in height. Thus it may cause deflection of buildings especially at the top of the structure. The top part of the building bends slightly when subjected to wind turbulence. Periodic oscillation of building may occur. As the frequency of oscillation of buildings is too high, in other words the buildings sway too much, it may cause human discomfort at the upper floor. Wind loads, therefore, need to be studied. Most of the building structural design codes consist of higher design pressures specified at higher elevation (Taranath 2005).

2.4 Human Perception of Motion Criteria for Tall Buildings Subjected to Wind

With the availability of newer and more efficient materials and construction methods, the trend is now moving forward to taller and lightweight structures. This has led to significant reductions in using traditional heavy masonry cladding and partition walls, which were effective in providing strong stiffness of structural frames. As a consequence of increased flexibility but potentially diminished damping and stiffness, the typical light and flexible modern tall buildings are much more responsive to dynamic exciting wind force (McNamara, et.al 1993). In the paper, it is also discussed that even the design may satisfactorily carry all loads to meet serviceability requirements; the resulting dynamic stresses may still be greater than static values. This is thus causing the structure suffer from levels of induced motions. It may disturb the comfort and equanimity of the occupants of the building.

From the point of view of the public, a building structure should remain stationary. It would be expensive to construct a building that would not move perceptibly in the worst wind flow or storm. Thus, some motion is inevitable in tall buildings. The design of tall buildings should concern with efficiently and effectively carrying the anticipated loads imposed upon the structure, serviceability as well as habitability issues. There are yet no generally accepted international standards for comfort criteria however it is also generally agreed that acceleration is the predominant factor in determining the nature of human response to vibration.

As a result, there has been a concerted effort to quantify acceleration levels that induce negative response in building occupants. Although it is generally found that the maximum lateral wind loading and deflection are in the along-wind direction, the maximum acceleration of the building, which is particularly important for human comfort, may often occur in the cross-wind direction. Table 2.2 illustrates how human behavior and motion perception are affected by different ranges of acceleration.

Table 2.2 Human Perception Levels

Range	Acceleration (m/sec^2)	Effects
1	< 0.05	Humans cannot perceive motion.
2	0.05 ~ 0.10	Sensitive people can perceive motion; Hanging objects may move slightly.
3	0.1 ~ 0.25	Majority of people will perceive motion; Level of motion may affect desk work; long-term exposure may produce motion sickness
4	0.25 ~ 0.4	Desk work becomes difficult or almost impossible; ambulation still possible
5	0.4 ~ 0.5	People strongly perceive motion; difficult to walk naturally; Standing people may lose balance.
6	0.5 ~ 0.6	Most people cannot tolerate motion and are unable to walk naturally.
7	0.6 ~ 0.7	People cannot walk or tolerate motion.
8	> 0.85	Objects begin to fall and people may be injured.

CHAPTER 3
METHODOLOGY

This section provides an outline showing the methodology in carrying out the research. The methodology is meant for the reader to have a clearer view and understanding on how this research will be carried out by the author to archive the objectives.

First and foremost, the concept of tall buildings (structural system, service core, wind load and comfort criteria) will be discussed so that the reader may have better understanding about tall building structures' design and analysis. A special purpose program, ETABS will be introduced in the research to analyze tall buildings. A trial run of a basic model in ETABS will be tested in order to understand the basic function of the software. This research is based on a case study collected from an on going local project in Kuala Lumpur so that the site and wind condition of the case study can be studied. The structural element of the case study will be recognized and modeled in ETABS. In fulfillment the objective of this research, a total of four extra cases will be proposed based on the case study. On the other hand, wind loading calculation will be based on the geometry and plan dimension of the case study, in the context of BS 6399-2-1997 code. Then sensitivity analysis for all the cases will be performed based on certain parameters (lateral stiffness, bending moment diagram, dynamic response). Finally all the measure parameters will be reviewed to obtain optimum structure criteria.

Figure 3.1 shows the flow chart of methodology. The flow chart will be further explained from Section 3.1 to 3.6.

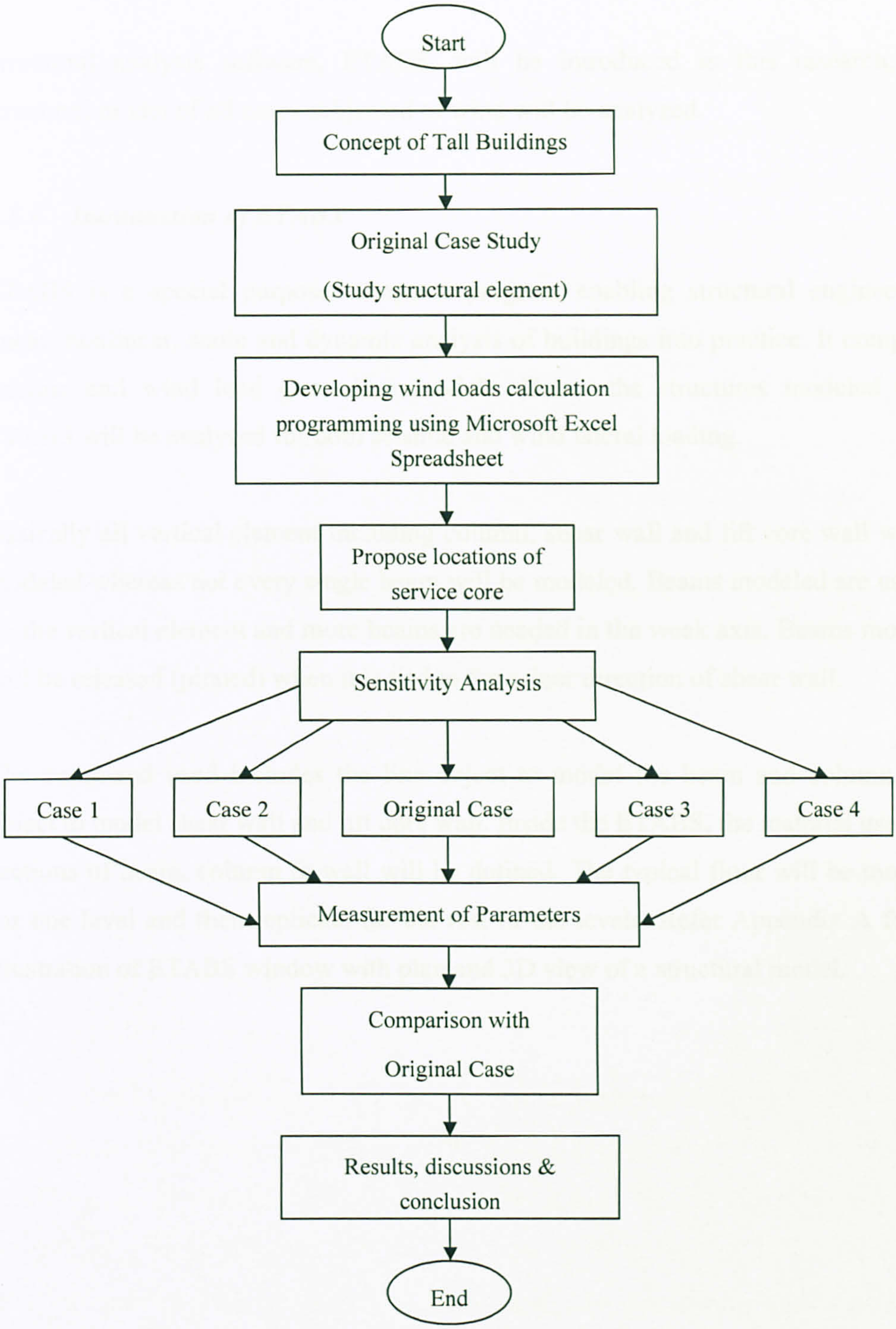


Figure 3.1 Methodology flow chart

3.1 Structural Model

Structural analysis software, ETABS, will be introduced in this research. The structural model of all cases subjected to wind will be analyzed.

3.1.1 Introduction of ETABS

ETABS is a special purpose computer program enabling structural engineer put linear, nonlinear, static and dynamic analysis of buildings into practice. It comprises seismic and wind load generation module. Hence the structures modeled using ETABS will be analyzed for both seismic and wind lateral loading.

Basically all vertical element including column, shear wall and lift core wall will be modeled whereas not every single beam will be modeled. Beams modeled are used to tie the vertical element and more beams are needed in the weak axis. Beams modeled will be released (pinned) when it is tied to the minor direction of shear wall.

The command used includes the line object to model the beam and column, area object to model shear wall and lift core wall. Inside the ETABS, the material used and sections of beam, column & wall will be defined. The typical floor will be modeled for one level and then replicate for the rest of the levels. Refer Appendix A for the illustration of ETABS window with plan and 3D view of a structural model.

3.2 Case Study

The case study is based on a mix-development tower located in the capital city of Malaysia, Kuala Lumpur. It is one of the towers of a mega project development sited on a 3.68ha freehold land beside Jalan Stonor and Lorong Kuda (Figure 3.2). The area of this mega development is surrounded by new high-end condominiums. The mix-development tower consists of retails and offices.

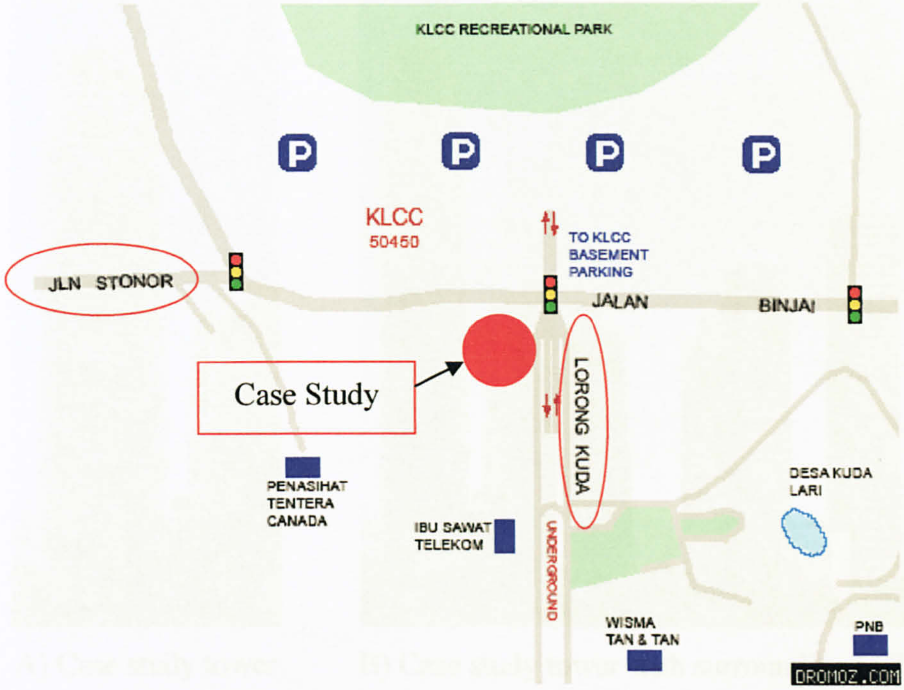


Figure 3.2 Location of case study

The mix-development tower is approximately 217 meters in height measured from ground level. The tower comprises of 50 floors. It will have a net lettable area of 689,000 square feet and a floor plate of 15,000 square feet. It will also have, among other things, a large banquet hall that can seat 1500 people at the basement level, double volume ceiling, pre-function lobby and two basements and a podium for parking. More specifically, the podium is up to level 11 which is a mixture of podium car park and commercial use. From basement 2 to level 2, there are retail, multi-purpose hall, gallery, lounge, etc. Like wise, podium car park is started from basement 2 to level 9. At level 10 and level 11, there are restaurant, food court, recreational area and gymnasium. From level 12 onwards up to level 50, the tower is mainly office area. Only few levels are mechanical and electrical (M&E) area.

The construction started in 2008 and is scheduled for completion in 2012. There are other components being developed in the area surrounding this 50-storey tower, including twin 30-storey 123-unit residences I, twin 43-storey 164-unit residences II, twin 30-storey suites, 38-storey suites I, 33-storey suites II, 1.5 acre of private park and niche lifestyle retail offerings spread over 80,000 square feet. Figure 3.3 shows the artist impression of the mix-development.

A) Case study tower B) Case study tower with surrounding buildings

Figure 3.3 Artist impression of case study

The geometric shape of the case study is the combination of rectangular and eclipse in shape. The podium is designed as rectangular shape while the tower is designed as eclipse shape (Appendix B).

The structural system used in this case study is perimeter circular reinforced concrete columns with centre core approach. This can be classified as a frame tube structural system. Within the region of the tower, only two main columns are placed in both ends of the service core. The columns dimension reduces as the height increases.

3.3 Wind Loading Calculation

Wind load calculation will be based on The British Standard BS 6399 Loading for Buildings, Part 2 (BS 6399 - 2). One out of two methods specified in BS 6399 – 2 will be identified to develop a programming using Microsoft Excel Spreadsheet. The wind load calculation will be based on the case study (Figure 3.4).

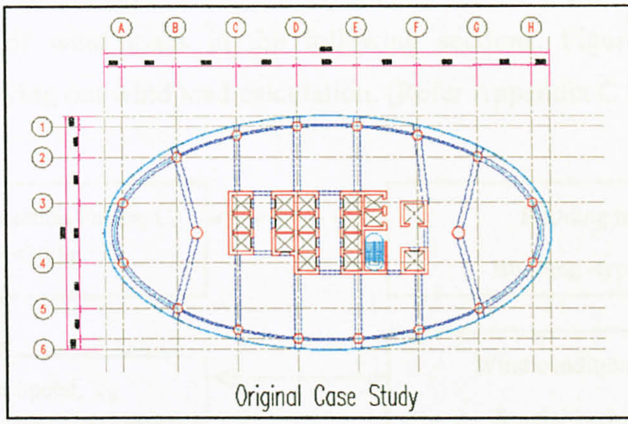


Figure 3.4 Original case study structural layout

3.3.1 Wind Loading Analysis (designed to BS 6399-2-1997)

According to The British Standard BS 6399 Loading for Buildings, Part 2 (BS 6399-2), there are two methods in carrying out the calculation for wind load. These include Standard Method and Directional Method.

Standard Method is basically a simplified method which can be calculated manually. The value of wind loads calculated will be more conservative because it uses worst combination factors. In the code, only buildings below 100 meters can be applied Standard Method. Most designers, however, usually apply Standard Method with buildings up to 200 meters by doing some extrapolation of the certain factors used. Like wise, Directional Method is more complex in the calculation as the value of wind loads will be more precise. It is recommended that wind load calculation based on Directional Method to be carried out with the implementation of computer software. A simple programming will be developed using Microsoft excel spreadsheet in carrying out the wind load calculation for the case study.

3.3.2 Standard Method

In BS 6399-2, wind load on the buildings are considered as static. Hence there is a factor called Dynamic Augmentation, C_r will be considered. This Dynamic Augmentation, C_r will be determined from the basic geometric and structural properties of the case study tall building. Together with the building height, H and building-type factor, K_b, this Dynamic Augmentation factor will be used to check whether the code can be applied. A brief description will be explained in carrying out the calculation of wind loads in the following sections. Figure 3.5 shows the flowchart of carrying out wind load calculation. (Refer Appendix C for details)

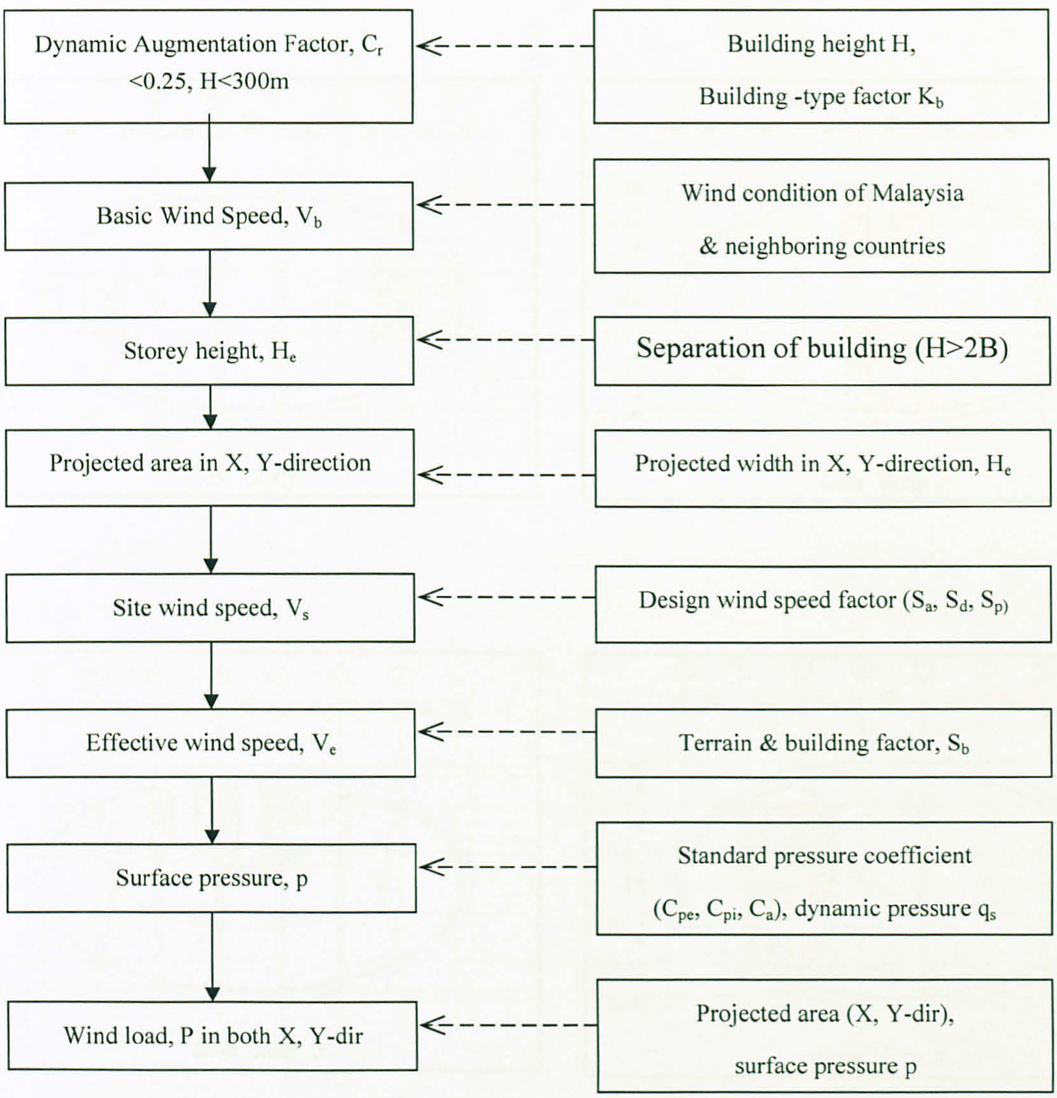


Figure 3.5 Flowchart illustrating wind loading calculation stages & criteria

3.4 Proposed Locations of Service Core

There are four proposed locations of service core for this research namely as case study 1 (CS1), case study 2 (CS2), case study 3 (CS3) and case study 4 (CS4). For CS1, the location of service core is moved apart to the side along X-axis while for CS2 the location of service core is moved apart to the side along Y-axis. On the other hand, CS3 and CS4 are asymmetrical cases. If check from the plan view, the service core for CS3 will be located at the upper end of the tower while service core for CS4 will be located at the left end of the tower. All these proposed locations of service core for all case studies are shown in Figure 3.6.

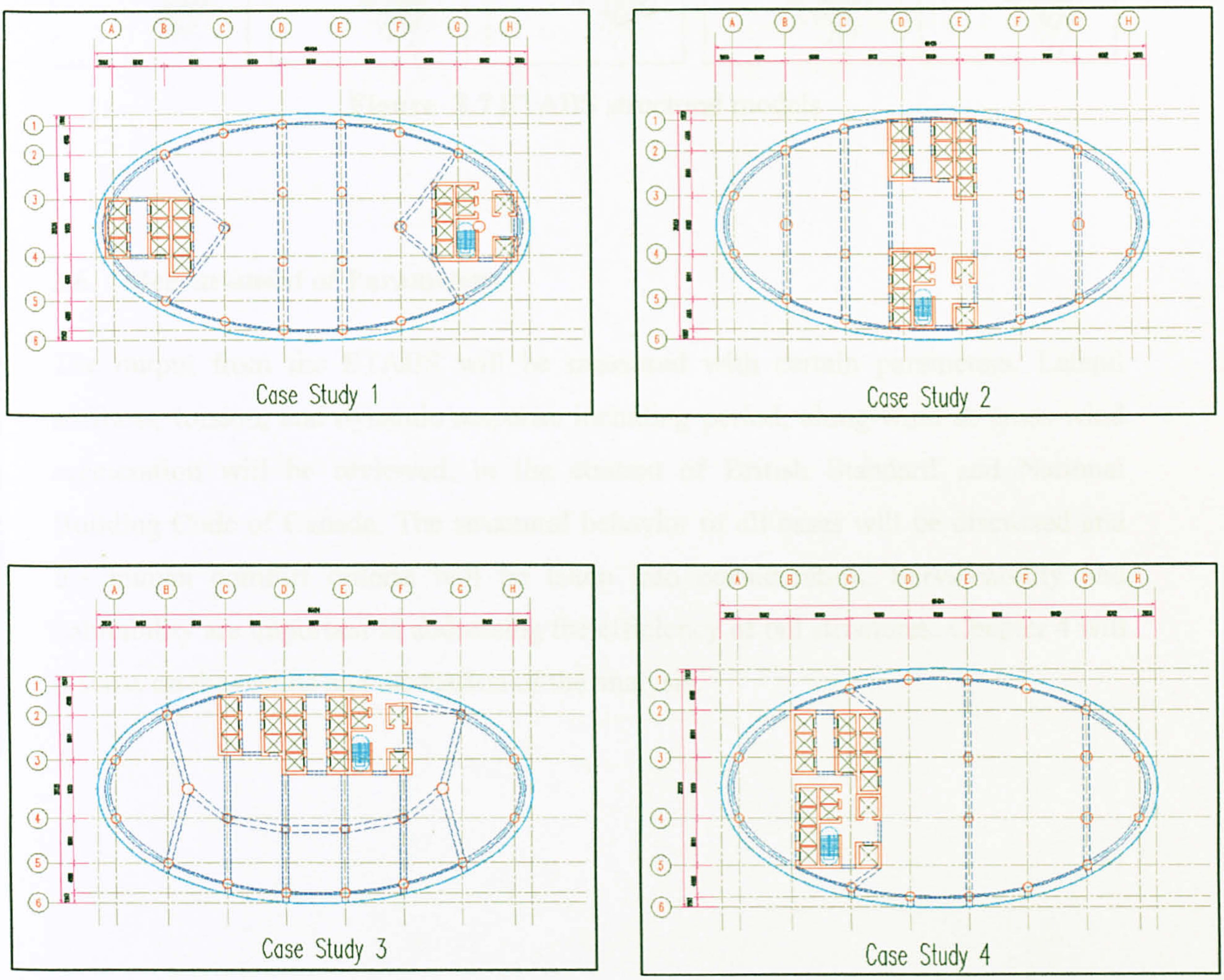


Figure 3.6 Proposed locations of service core

3.5 Sensitivity Analysis

There are five cases have been modeled using ETABS. These include the original case study, CS1, CS2, CS3 and CS4. Figure 3.7 shows the structural models for all case studies.

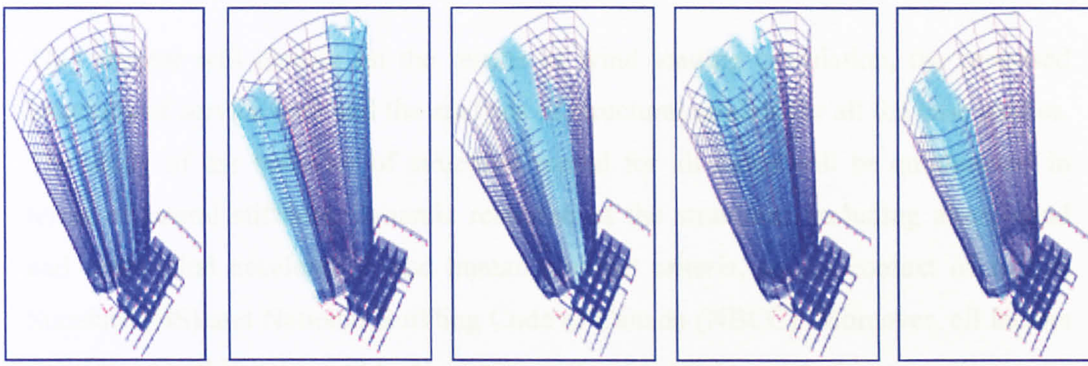


Figure 3.7 ETABS structural models

3.6 Measurement of Parameters

The output from the ETABS will be measured with certain parameters. Lateral stiffness, torsion, and dynamic response including period, along-wind & cross-wind acceleration will be reviewed, in the context of British Standard and National Building Code of Canada. The structural behavior of all cases will be discussed and the human comfort criteria will be taken into consideration. Serviceability and habitability are important in addressing the efficiency of tall structures. Chapter 4 will discuss on the results and discussion of the analysis.

CHAPTER 4
RESULTS AND DISCUSSIONS

This chapter will discuss on the results of wind loading calculation, the proposed locations of service core and the analysis of structural models for all the case studies. The study of the behavior of structural model for all cases will be emphasized in terms of lateral stiffness, dynamic response of the structures including along-wind and cross-wind acceleration and human comfort criteria, in the context of British Standard (BS) and National Building Code of Canada (NBCC). Moreover, all factors considered will be reviewed to discuss on optimum structure criteria.

4.1 Wind Loading

The wind load calculation for the 50-storey mix-development retail office tower at Jln. Stonor, Kuala Lumpur is based on BS 6399-2-1997. The basic wind speed used in the wind load calculation is 15 m/s (refer Appendix D).

From the calculation result, it can be observed that wind load in Y-direction is more critical than X-direction. The wind load for each floor is calculated by multiplying the surface pressure with projected area, either in X-direction or Y-direction. Projected area is where the area of one particular floor which will be subjected to wind pressure. In other words, the projected area is the storey height multiplied to the length of that particular floor. Since the projected area of the tower in Y-direction is larger than projected area in X-direction thus causing the wind load in Y-direction will be larger.

The wind load is increasing steadily from the base of the tower towards to the upper floors. Nevertheless, for certain levels, including podium level (Level 1 & 2), level 11, level 12, level 19, level 36, level 49, level 50 and lift motor room (level 51), the wind loads recorded for all these levels are larger compared to the floor below and above of each level. This is due the storey height for all these levels are larger. Figure 4.1 shows the graph of the cumulative storey height to the wind load in Y-direction. Since the wind load is larger in Y-direction, hence the recorded values will be used to analyze the structural models in ETABS.

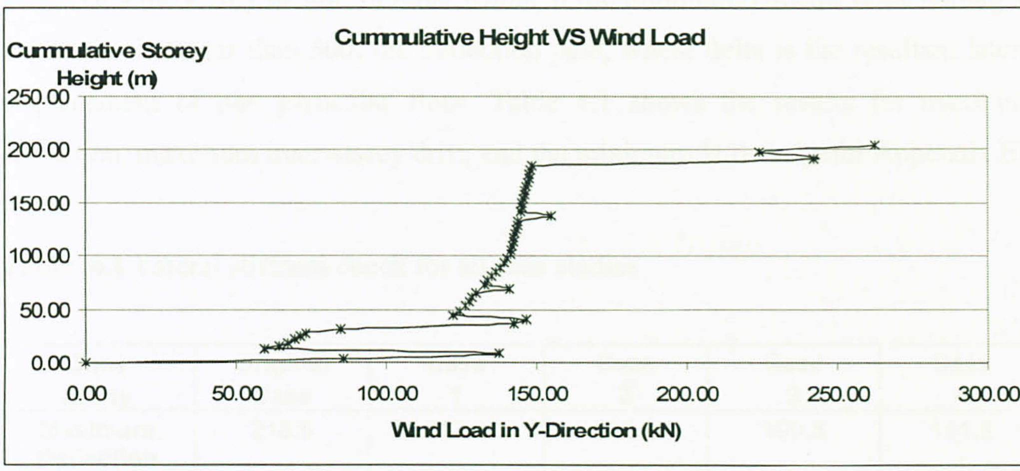


Figure 4.1 Graph of cumulative storey height vs wind load in Y-direction

From the graph, it can be observed that the maximum wind load is at the highest floor of the tower. The value recorded is 262.72 kN at level 51, which is a lift motor room.

4.2 Measurement of Parameters and Observations

In a tall wall-frame structure, in order to optimize the desirable effect of the wall-frame interaction, it is desirable to aim not only to achieve significant reductions in the deflections but also the reduction of the wall moments. The control of lateral deflections is of particular importance for modern buildings. This is because the stiffness due to heavy internal partitions and outer claddings has largely replaced. Nonetheless, if the deflection is kept within the accepted limits, dynamic comfort criteria are not necessarily satisfactory. Thus, acceleration of structure is checked with human perception level. When building is subjected to twist, torsional stiffness of the structure is significant as part of the torsional resisting system.

4.2.1 Lateral Stiffness

One simple parameter that affords an estimate of the lateral stiffness of a building is the drift index, defined as the ratio of the maximum deflection at the top of the building to the total height.

British Standard 8110 Part 2: Code of practice for special circumstances-1985 is the guide for the lateral stiffness check. According to section 3.2.2.2 in the code, the relative lateral deflection in any one storey under wind load should not exceed H/500, where H is the storey height. In other words, if the minimum H/delta value among all the stories is larger than 500, the deflection pass, where delta is the resultant lateral displacement of one particular floor. Table 4.1 shows the results for maximum deflection, maximum inter-storey drift, and the minimum H/delta (refer Appendix E).

Table 4.1 Lateral stiffness check for all case studies

Case Study	Original Case	Case 1	Case 2	Case 3	Case 4
Maximum Deflection (mm)	218.5	217.3	205.8	190.3	151.6
Level	51	51	51	51	51
Maximum Drift (mm)	1.29	1.29	1.23	1.12	2.08
Level	41,42,43,44	35	31,32,33	31,32	19
Minimum H/delta	723	736	777	842	727
Level	35	35	35	35	51

From Table 4.1, it can be observed that the maximum deflection occurs at level 51, where it is a lift motor room. All proposed case studies have lower maximum deflection compared to original case. The biggest maximum deflection difference is CS4 and original case, which is 66.9mm. On the other hand, checking for the H/delta value, all cases meet the requirement of BS 8110. The minimum H/delta value is recorded at level 35 for all cases except for CS4, which is at level 51. In other words, level 35 is the critical level for original case, CS1, CS2 and CS3 while level 51 is the critical level for CS4. Critical level is the level which has the lowest serviceability limit. Figures 4.2, 4.3 and 4.4 illustrate the graph of cumulative storey height versus deflection, in X-direction, Y-direction and the resultant deflection respectively.

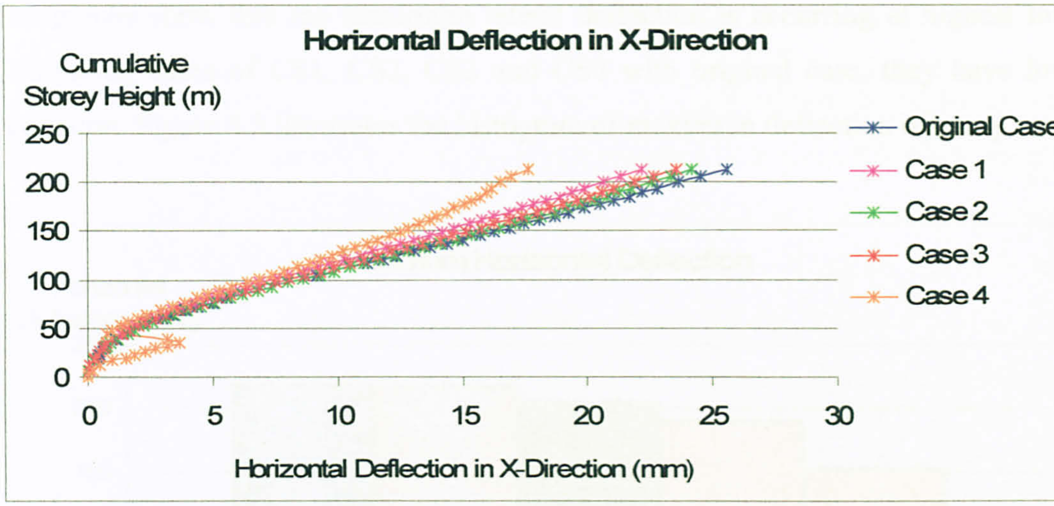


Figure 4.2 Horizontal deflection in X-direction

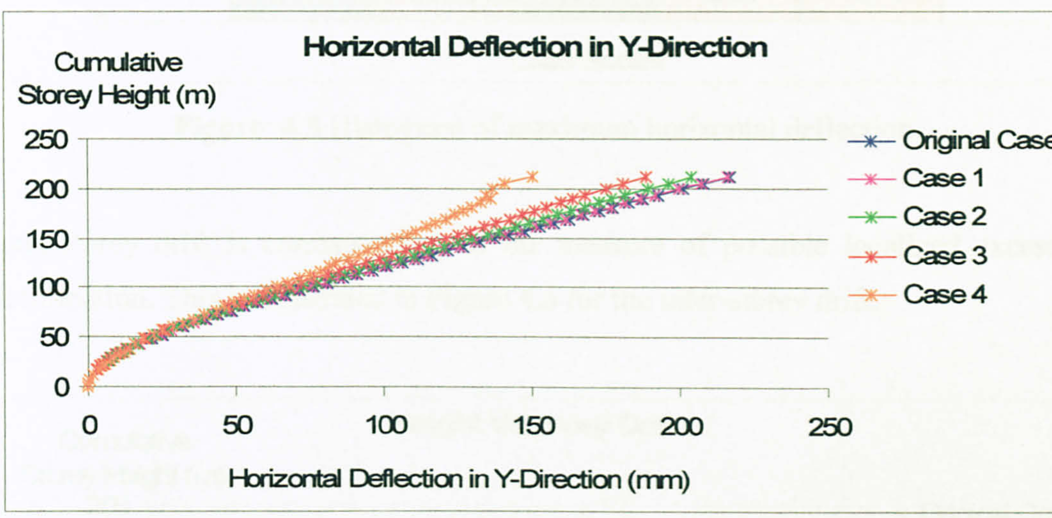


Figure 4.3 Horizontal deflection in Y-direction

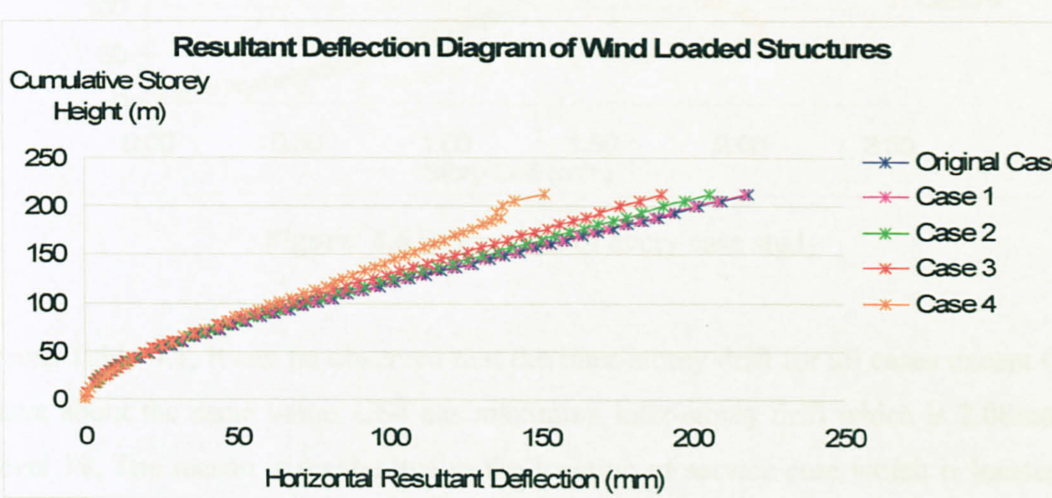


Figure 4.4 Resultant horizontal deflection

The graphs show that the maximum lateral deflection is occurring at highest level. Comparing cases of CS1, CS2, CS3 and CS4 with original case, they have lower deflection. Figure 4.5 illustrates the histogram of maximum deflection of every case.

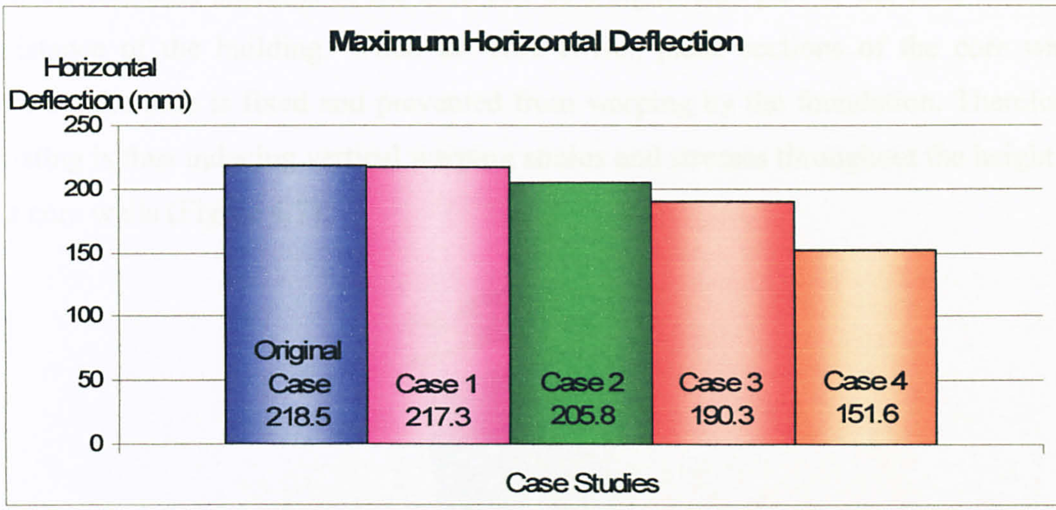


Figure 4.5 Histogram of maximum horizontal deflection

Inter-storey drift is corresponding to the measure of possible localized excessive deformation. This is illustrated in Figure 4.6 for the inter-storey drift.

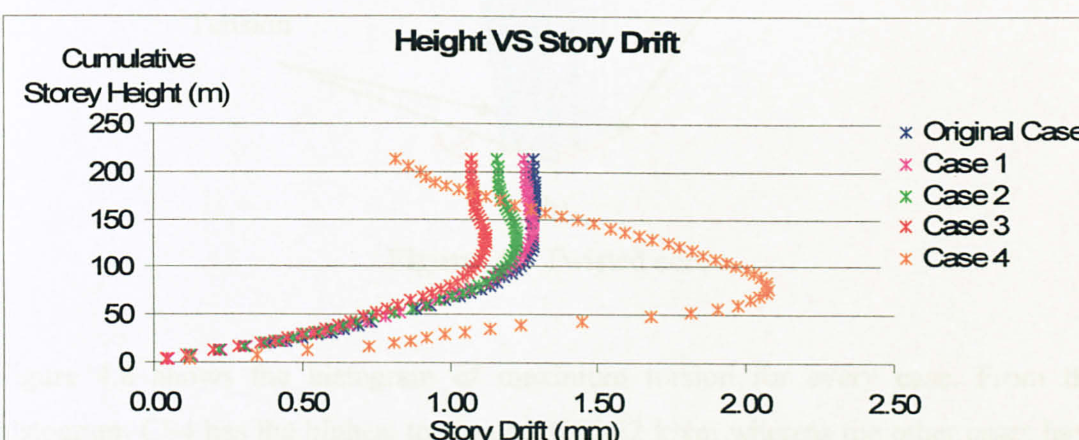
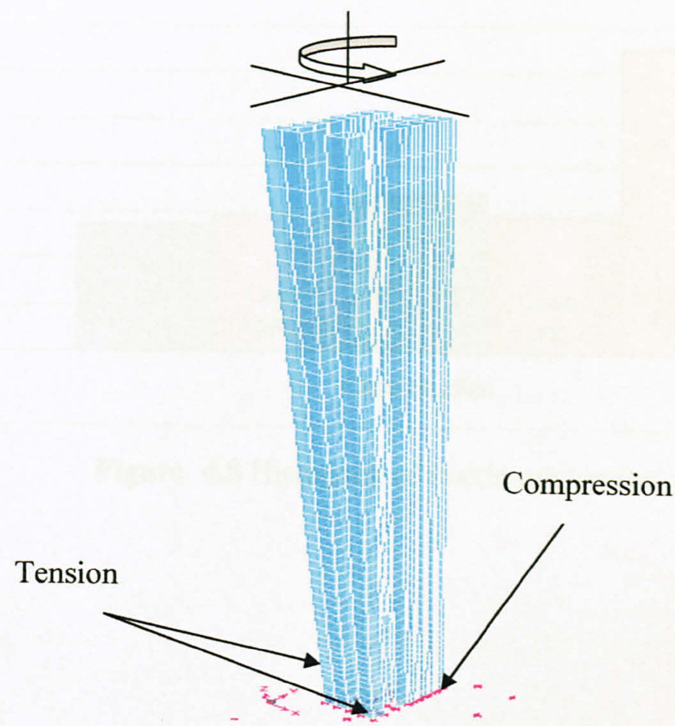


Figure 4.6 Storey drift of every case study

From Table 4.1, it can be observed that the inter-storey drift for all cases except CS4 have about the same value. CS4 has maximum inter-storey drift which is 2.08mm at level 19. The reason is maybe due to the location of service core which is located at one side (along X-axis) of the tower. Hence the torsional deflection may take place thus causing the storey not only deflect laterally but torsionally as well.

4.2.2 Torsion of Structures

Torsion on a building is resisted by shear in the vertical components and by the shear and warping torque resistance of the core. If a building is subjected to twist, as many are, the torsional stiffness of the core can be a significant part of the total torsional resistance of the building. When the core twists, plane sections of the core warp because the base is fixed and prevented from warping by the foundation. Therefore, twisting is thus inducing vertical warping strains and stresses throughout the height of the core walls (Figure 4.7).



(b)

Figure 4.7 Twisted core

Figure 4.8 shows the histogram of maximum torsion for every case. From the histogram, CS4 has the highest torsion of 3265.32 kNm whereas the other cases have about the same torsion ranged from 1360 kNm to 1720 kNm.

Referring to Figure 3.6 for the structural plan view, the location service core for CS4 is at one end of the tower. Hence the center of mass of the tower is located at nearer to the core structure. When the wind is acting on the tower elsewhere than through the center of gravity, the tower will twist and warp as well as bend.

On the other hand, original case has the lowest torsion because the service core is located in the center of the tower thus the center of mass of the tower will be at somewhere nearer to the center. For CS1, CS2 and CS3, the torsions recorded are still smaller than CS4. Nonetheless, all case studies twist and warp when the structures are subjected to wind. This may be due to the center of mass is not exactly in the center of the tower.

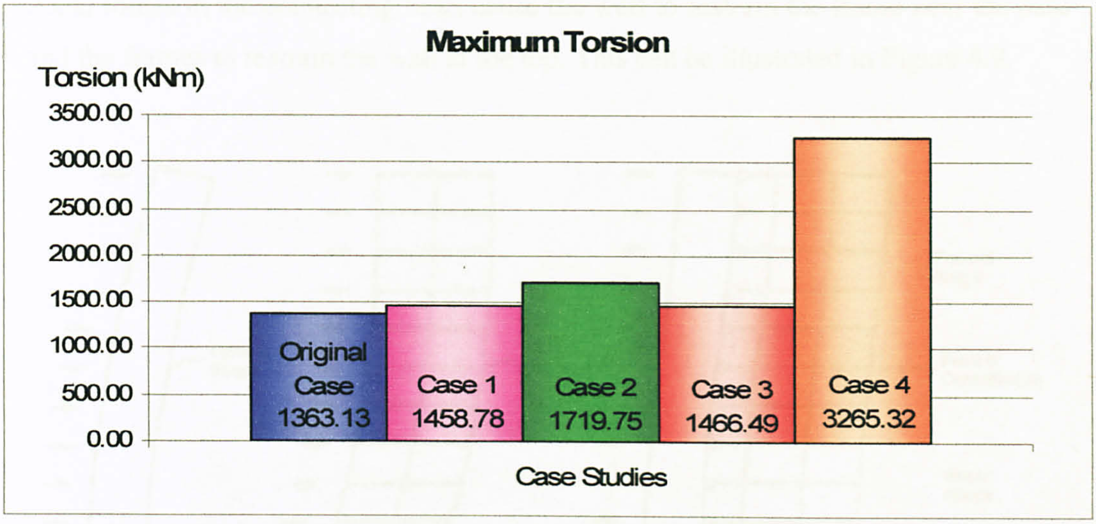


Figure 4.8 Histogram of maximum torsion

4.2.3 Service Core Wall Bending Moment

The wall deflects in a flexural mode with concavity downwind and a maximum slope at the top, while frame deflects in a shear mode with concavity upwind and a maximum slope at the base.

When the wall and frame are connected together, the deflected shape of the composite structure has flexural profile in the lower part and a shear profile in the upper part. Axial forces in the connecting links cause the wall to restrain the frame near the base and the frames to restrain the wall at the top. This can be illustrated in Figure 4.9.

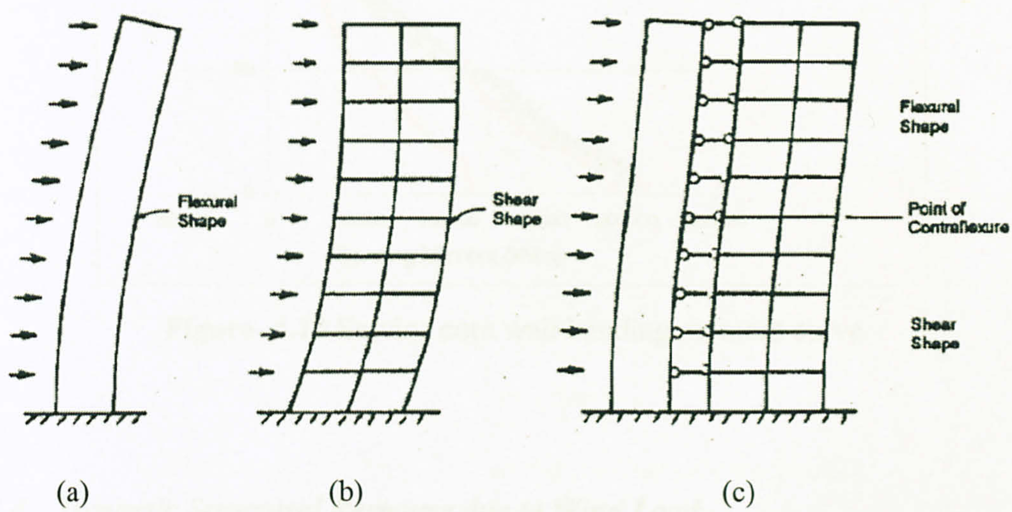


Figure 4.9 (a) Wall subjected to uniformly distributed wind load; (b) frame subjected to uniformly distributed wind load; (c) wall-frame structure subjected to wind load

The effects of wall-frame interaction can be illustrated using the curves for deflection and also wall moment curve. The service core wall bending moment curve (Figure 4.10) indicates the reversal in curvature with a point of inflexion, above which the wall moment is opposite in sense to that in a free cantilever. In order to achieve optimum structure for wall-frame system, reduction in wall bending moment is one of the criteria.

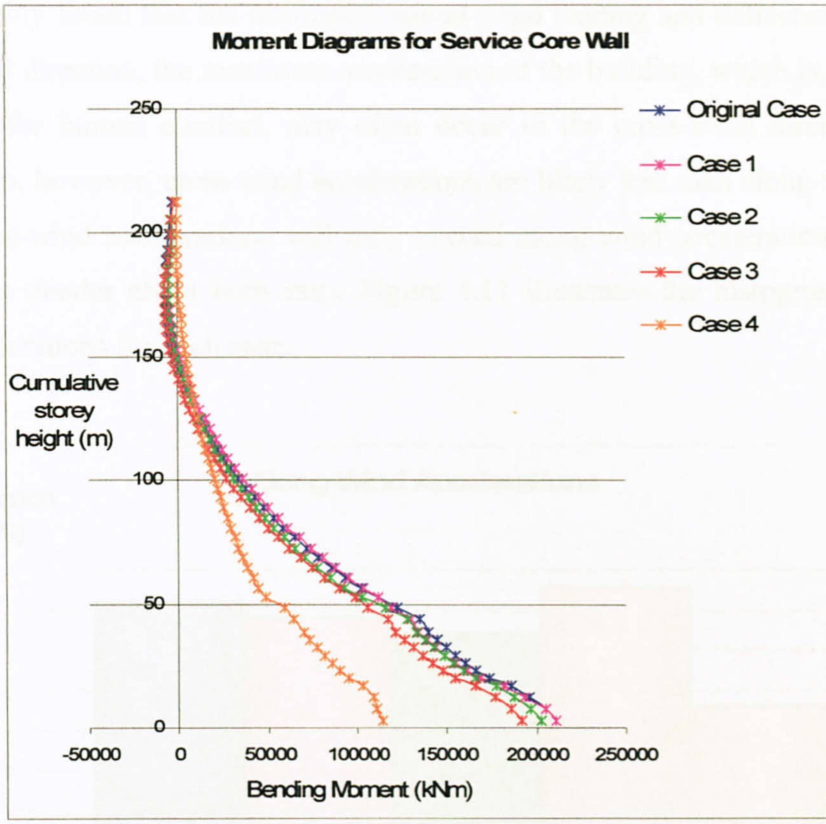


Figure 4.10 Service core wall bending moment curve

4.2.4 Dynamic Structural Response due to Wind Load

When considering the response of a tall building to wind load, both along-wind and cross-wind motions will be considered (Figure 2.4). Cross-wind response may be of particular importance with regard to the comfort of the occupants. It is generally agreed that acceleration is the predominant parameter in determining the nature of human response to vibration. Hence, both along-wind and cross-wind acceleration have been computed (refer Appendix F). Table 4.2 shows the results of accelerations.

Table 4.2 Accelerations of along-wind and cross-wind direction

Case studies	Along-wind (m/s^2)	Cross-wind (m/s^2)
Original Case	0.036	0.007
Case 1	0.034	0.008
Case 2	0.032	0.008
Case 3	0.038	0.007
Case 4	0.023	0.009

It is generally found that the maximum lateral wind loading and deflection are in the along-wind direction, the maximum acceleration of the building, which is particularly important for human comfort, may often occur in the cross-wind direction. From observation, however, cross-wind accelerations are likely less than along-wind in this case. Cross-wind accelerations will only exceed along-wind accelerations when the building is slender about both axes. Figure 4.11 illustrates the histogram of along-wind accelerations for each case.

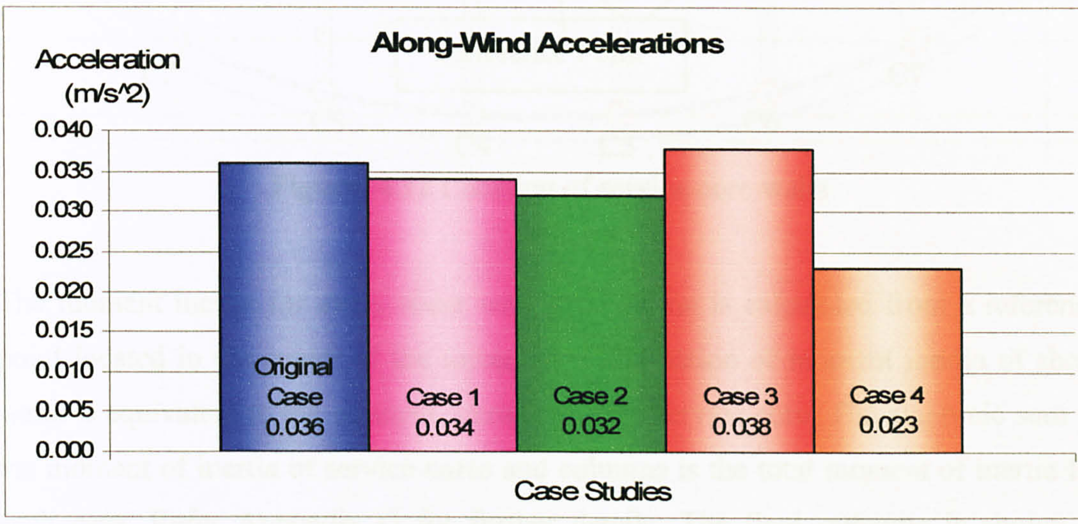


Figure 4.11 Along-wind accelerations of case studies

It can be observed that CS4 has the lowest along-wind acceleration ($0.023 m/s^2$) while along-wind accelerations for original case, CS1, CS2 and CS3 are more than $0.03 m/s^2$. Comparing to human perception levels (Table 2.2), however, both along-wind and cross-wind accelerations for all case studies are fall in range 1, where acceleration is less than $0.05 m/s^2$. The effect of buildings fall under range 1 is where occupants of the structure will not perceive motion.

4.2.5 Moment of Inertia

The moment inertia of structures about X-axis, Ixx is computed for every case. There are five service core walls for every case. All five service cores are labeled as LCW 1, LCW 2, LCW 3, LCW 4 and LCW 5. In carrying out the calculation, each service core wall is split into shear wall namely as wall 1, wall 2 and so on. Figure 4.12 shows the location of reference point and the labeling of components.

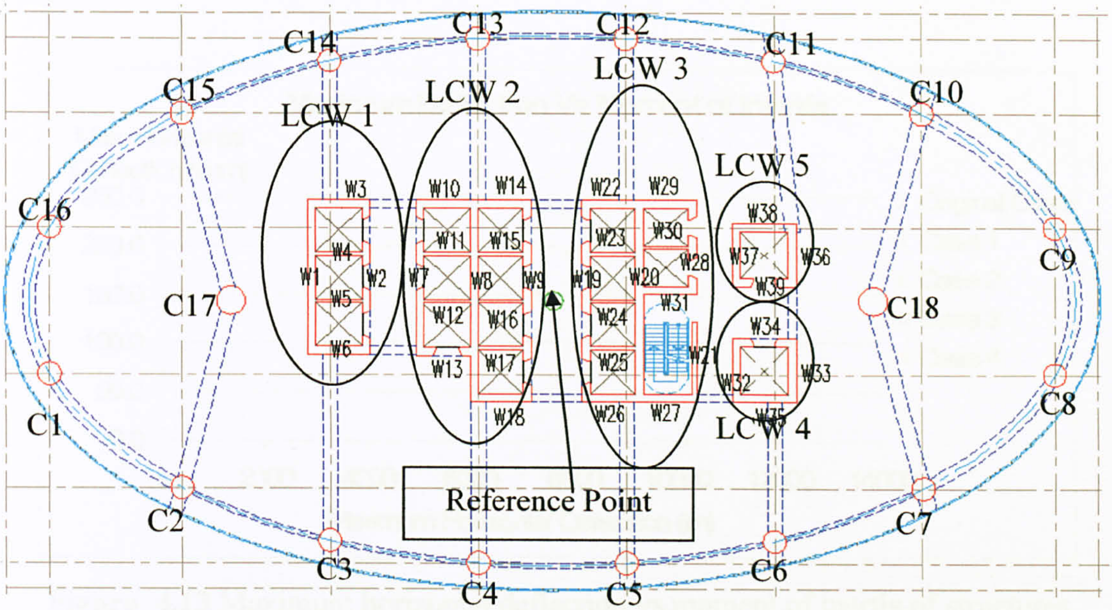


Figure 4.12 Labeling of service core walls

The moment inertia for every shear wall and column is calculated from a reference point located in the center of the tower. The summation of moment inertia of shear walls is equivalent to the moment inertia for each service core. The algebraic sum of the moment of inertia of service cores and columns is the total moment of inertia for each case. Refer Appendix G for further details. The final outcome is shown in Table 4.3.

Table 4.3 Moment of inertia of structures with corresponding maximum deflection

Case Studies	Moment of Inertia, Ixx (m^4)						Total Ixx (m^4)	Max. Deflection (mm)
	LCW 1	LCW 2	LCW 3	LCW 4	LCW 5	Column		
Original Case	158.780	376.686	339.484	136.210	18.089	3849.921	4879.170	218.5
Case 1	130.565	393.611	329.103	97.018	27.366	3909.867	4887.530	217.3
Case 2	1893.650	3173.515	2534.283	1367.595	98.897	2388.798	11456.738	205.8
Case 3	1453.843	2578.735	953.217	135.056	252.040	2574.295	7947.186	190.3
Case 4	734.968	1287.180	1012.884	689.582	18.747	3605.301	7348.662	151.6

From Table 4.3, it can be observed that CS2 has the highest moment of inertia which is 11457 m^4. Then it is followed by CS3 and CS4 with moment inertia of 7947 m^4 and 7349 m^4 respectively. For both original case and CS1, the moment inertia for service core is approximately 4890 m^4. Figure 4.13 shows the relationship of maximum deflection and moment of inertia of the structures.

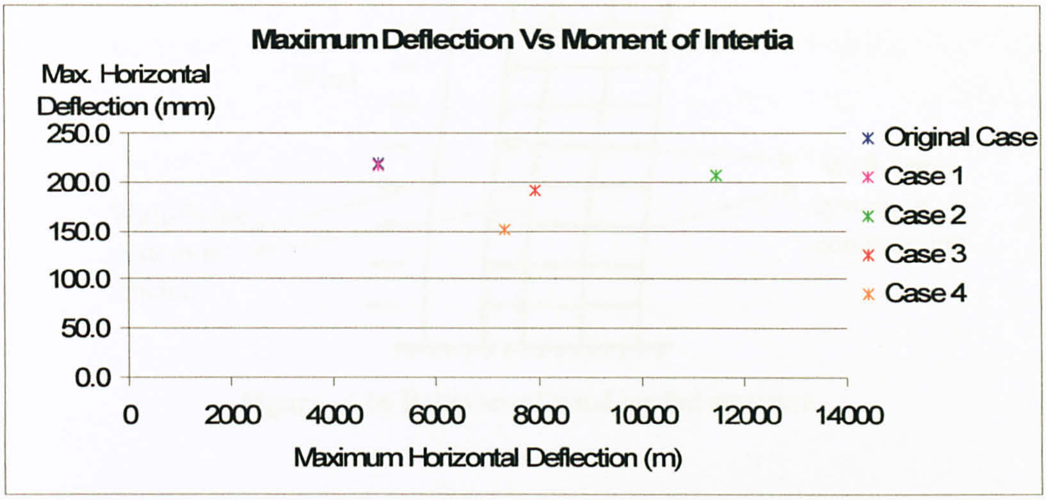


Figure 4.13 Maximum horizontal deflection vs moment of inertia of structures

The moment of inertia of the structures is inversely proportional to the deflection. In other words, higher value of moment of inertia of the structure will have lower deflection. From the observation in Figure 4.13, however, although CS4 has the lowest horizontal deflection, it does not necessarily reflect the highest moment of inertia. Moreover, CS2 has the highest of moment of inertia but the horizontal deflection is not the lowest. From here, the moment of inertia may not be significant in resisting lateral load.

4.2.6 Column and Wall Forces

When the structure is subjected to wind load in either X-direction or Y-direction, the structure will deflect parallel to the direction of the wind blow. This is illustrated in Figure 4.14. The front face of the structure which is subjected to the wind load (windward), the structural elements including columns and walls are in tension. On the other hand, the structural components at the back face of the structure (leeward) are in compression.

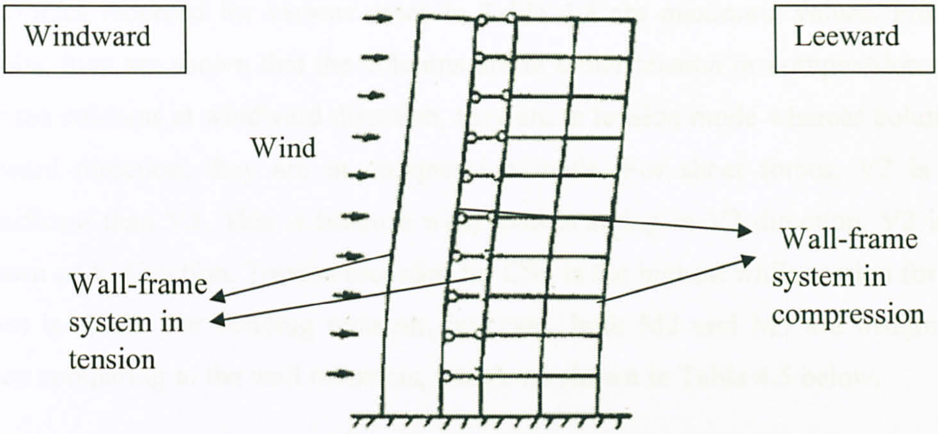


Figure 4.14 Behavior of wind loaded structure

The analysis results for the structural models of all cases from ETABS are tabulated in Table 4.4 (column forces) and Table 4.5 (wall forces). Included in the tables are the axial forces (either in tension or compression), torsion, shear forces and moments for both columns and service core walls. The global axis for all structural components is based on right-hand-rule.

Table 4.4 Column forces

Case	Axial Load, P (kN)		Shear, V (kN)		Torsion, T	Moment, M (kNm)	
Studies	Compression	Tension	V2	V3	(kNm)	M2	M3
Original Case	-2392.52	2222.92	180.89	-38.74	-21.586	246.153	-758.69
Level, Label	Basement 1, C77	L11, C47	L4, C68	L20, C77	L10, C62	Basement 1, C54	Basement 1, C76
Case 1	-1588.06	4200.79	-154.8	-76.1	-11.803	256.888	-770.232
Level, Label	L2, C80	L2, C54	L9, C55	L4, C76	L10, C62	Basement 1, C48	Basement 1, C78
Case 2	-2365.61	2095.76	171.78	68.93	17.906	228.493	-779.992
Level, Label	L2, C81	L2, C48	L4, C72	L10, C42	L20, C63/C64	Basement 1, C52	Basement 1, C76
Case 3	-876.03	1768.69	175.16	-36.91	-21.993	232.433	-713.912
Level, Label	Basement 1, C66	L11, C47	L4, C72	L5, C79	L10, C65/C66	Basement 1, C54	Basement 1, C61
Case 4	-3299.44	3041.54	-288.21	146.53	417.603	553.785	-1788.703
Level, Label	L2, C76	L2, C50	L11, C57	L10, C13	L12, C57/C69	Basement 1, C48	L11, C57

*Note:

[-] Value in negative sign shows that the forces act in opposite direction

All forces recorded for various cases in Table 4.4 are maximum values. From the results, they are shown that the columns are in either tension or compression mode. For the columns at windward direction, they are in tension mode whereas columns at leeward direction, they are in compression mode. For shear forces, V2 is more significant than V3. This is because wind load is acting in V2 direction. V2 is also known as Y-direction. Torsion recorded for CS4 is the highest while torsion for other cases is small. For bending moment, however, both M2 and M3 are insignificant when comparing to the wall moments, which are shown in Table 4.5 below.

Table 4.5 Service core wall forces

Case	Axial Load, P (kN)		Shear, V (kN)		Torsion, T	Moment, M (kNm)	
Studies	Compression	Tension	V2	V3	(kNm)	M2	M3
Original Case							
LCW1	-	439.85	964.66	-7.38	-58.30	-1362.18	70605.26
LCW2	-	123.58	2114.13	38.54	-35.48	9645.95	188101.77
LCW3	-2620.12	-	1742.13	-30.50	-1363.13	-8546.35	211027.03
LCW4	-	6366.03	2.27	253.70	17.19	6484.05	558.80
LCW5	-3384.25	-	254.85	1.06	13.46	-698.44	6489.17
Case 1							
LCW1	-586.14	-	850.04	-9.25	6.54	-1119.95	69121.43
LCW2	-2207.70	-	1935.07	44.21	161.90	10445.41	186409.40
LCW3	-5298.60	-	1899.30	-13.59	-1458.78	-8074.62	211011.30
LCW4	-	5985.00	4.61	276.50	28.77	6731.23	505.76
LCW5	-4139.36	-	277.78	4.81	25.84	-565.99	6736.32
Case 2							
LCW1	-1449.66	-	1004.60	-40.76	-133.96	-1613.56	68006.86
LCW2	-2648.65	-	2047.96	-32.47	-389.59	7836.71	179064.89
LCW3	-473.07	-	1795.82	24.33	-1719.75	-6918.90	202733.59
LCW4	-	6619.07	-8.82	249.62	-23.98	6196.93	311.53
LCW5	-2772.76	-	253.78	0.99	23.70	-611.33	6195.73
Case 3							
LCW1	-2254.25	-	968.06	-20.27	-42.56	-1213.365	65162.889
LCW2	-3950.96	-	2098.15	34.04	-22.787	8515.309	172807.819
LCW3	-6709.47	-	1756.71	-8.99	-1466.49	-8725.868	192122.074
LCW4	-	3706.35	1.47	253.29	17.682	6049.727	542
LCW5	-4443.92	-	254.65	2.47	16.717	-705.291	6053.395
Case 4							
LCW1	-5722.26	-	820.60	69.95	945.35	3115.98	34074.08
LCW2	-11595.07	-	2132.32	346.62	3265.32	22015.08	135139.33
LCW3	-	6473.92	937.09	-69.82	1001.73	-12815.65	114027.38
LCW4	-	5344.36	42.06	237.01	41.80	5250.79	2694.17
LCW5	-	5807.04	315.12	-8.76	202.08	9251.43	2785.04

*Note:

[-] Value in negative sign shows that the forces act in opposite direction

From Table 4.5, some service core walls are in tension, some are in compression as well. This is how the core walls behave when they are subjected to wind load. Furthermore, larger shear forces are recorded in V2 direction as well. Again this is due to the wind load which is subjected in the major axis. For torsion, CS4 has the highest torsion value. Comparing the wall moment to column moment, service core wall has larger moments. All the bending forces are transferred to service core walls which are then carried down to the foundations. The structure will become more stiffen when the number of walls is increased. It can be observed that moment in M3 direction is more significant than M2. This is because the walls resist bending about M3 direction when the wind is subjected in M2 direction. M2 is also known as Y-direction. Figure 4.15 illustrate the axes of 2 and 3 of components.

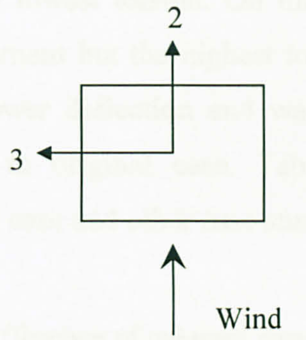


Figure 4.15 Principal axes of structural components

Appendix H provides figures with labeling of the locations of the structural components with maximum forces.

4.3 Comparison of Case Studies

After measuring the results with certain parameters, all case studies reflect different behavior of structure. The change of orientation of service cores has impact in the stiffness and dynamic responses of the buildings. Hence a matrix table of the analysis results including deflection, wall bending moment, torsion, moment inertia of core wall and along-wind acceleration is used to see the difference of every case. Table 4.6 shows the matrix table of case studies.

Table 4.6 Matrix table of case studies

Case Studies	Deflection (mm)	Bending Moment of Service Core (kNm)	Torsion (kNm)	Moment of Inertia of Structure Ixx (m^4)	Along-Wind Acceleration (m/s^2)
Original Case	218.5	211027	1363.13	4879.17	0.036
Case 1	217.3	211011	1458.78	4887.53	0.034
Case 2	205.8	202734	1719.75	11456.74	0.032
Case 3	190.3	192122	1466.49	7947.19	0.038
Case 4	151.6	114027	3265.32	7348.66	0.023

From matrix table, original case has the highest deflection and bending moment of service core but it has the lowest torsion. On the other hand, CS4 has the lowest deflection and bending moment but the highest torsion. For CS1, CS2 and CS3, all these case studies have lower deflection and wall moment as well but they have higher torsion compared to original case. Table 4.7 shows the percentage of difference between original case and other case studies.

Table 4.7 Percentage of difference of original case with other case studies

Case Studies	Percentage of reduction (%)		Percentage of increase (%)
	Deflection	Wall Moment	Torsion
Case 1	0.55	0.01	7.02
Case 2	5.81	3.93	26.16
Case 3	12.91	8.96	7.58
Case 4	30.62	45.97	139.55

It is significant to have reduction in deflection and wall bending moment for an optimum wall-framed structure. Table 4.7 illustrates that deflection and wall moment of CS4 has reduced 30.62% and 45.97% respectively compared to original case. Besides this, however, torsion of CS4 has increased 140% compared to original case. This is mainly due to the location of service core in CS4 is located at one side of the tower thus causing the center of mass of the tower is not in the center. When wind load is subjected to the structure of CS4, the tower twists.

For other cases (CS1, CS2 and CS3), the reduction of deflection and wall moment are not as significant as CS4. The torsion value, however, has slightly increased compared to original case. This is due to the change of location of service core will affect the center of mass of the structure as well.

Furthermore, the moment of inertia of structure is the algebraic sum of moment of inertia of walls and columns. CS2 has the highest moment of inertia. This is because the location of service core is split into two and located along Y-axis. It is thus causing the distance from the centroid of walls to the reference point which is located at the center of the tower is larger. On the other hand, the moment of inertia for original case and CS1 is about the same. Basically, the distance from centroid of walls to reference point is about the same for both original case and CS1. Case studies of CS3 and CS4 have large moment of inertia too. This is again due to the location of service core thus causing the distance from centroid of walls to reference point is large. The distance has the biggest effect in the calculation for moment of inertia because wall thickness, length, depth and area are the same for all case studies.

It is known that moment of inertia of structure is inversely proportional to deflection. In other words, if the moment of inertia is higher, the deflection is lower. In this project, however, it is found that the moment of inertia has lesser significance in influencing the deflection. Although CS2 has the highest moment of inertia, CS2 does not reflect that it has the lowest deflection.

For considering human comfort criteria, both along-wind and cross-wind accelerations have been computed for every case study. The along-wind acceleration is taken into consideration because it has higher acceleration compared to cross-wind direction. From the observation, CS4 has the lowest along-wind acceleration which is $0.023 m/s^2$. Nonetheless, although original case, CS1, CS2 and CS3 have higher along-wind acceleration, they are fall under range 1 of human perception level where range 1 defines that human do not perceive any motion of the structures.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Most of the time, architects and structural engineers have compromise in determining the most suitable and economical structural system for high rise structures. Architects have to meet the client's expectation from the point of view of aesthetic values and maximize space usage of the structures. Therefore, structural engineers are required to design the structural arrangement in the sense that subservient to the architectural layout. Thus, this will lead to a less-than-ideal structural solution.

For high rise buildings, it is essentially to consider lateral load. The lateral load resisting system in most high rise structures around Asia Pacific is core wall. Hence, this project is to study the significance of different orientations of service core in tall buildings. The behavior of the structures is discussed on its lateral stiffness, dynamic response and human comfort criteria.

A case study located in Kuala Lumpur has been adopted. The case study is a wall-framed structure. It is a proposed 50-storey retail office tower with approximate height of 217 meters. Wind load is taken into consideration because it is more significant in Malaysia.

There are four proposed orientation of service cores for the case study. The structural models of every cases namely as original case, CS1, CS2, CS3 and CS4 are analyzed in ETABS. The analysis is based on British Standard and National Building Code of Canada.

In high rise structure, primary concern is given to lateral stiffness and dynamic response. Tall buildings are vulnerable to lateral load attack thus causing swaying and deflection of structures. When the building sways too much, it will have big impact in human comfort and also the serviceability of the building.

From the analysis results, the behavior of structures subjected to wind load has been studied on different orientation of service core. Different orientation of service core will have big impact in the lateral stiffness, wall moment and torsion. Among the five case studies (original case, CS1, CS2, CS3 and CS4), CS3 is found that it is the optimum structure. The deflection and wall moment has reduced 12.91% and 8.96% respectively compared to original case. For torsion, it has slightly increased 7.58% as compared to original case. For CS4, however, although CS4 has reduced the most in deflection and wall moment, which are 30.62% and 45.97% respectively, CS4 has increased 140% in torsion. Hence, an optimum structure should have not only reduction in deflection and moment, but small torsion as well. The eccentricity of proposed location of service core should be limited. This is to ensure the building will not twist too much.

Comparing both original case and CS3, although CS3 has the lowest deflection and wall moment, original case has been adopted for most tall buildings. This is maybe due to the client's requirement or the internal function of structure requirement.

The analysis also shows that the moment of inertia is not as significant as the structural system in resisting lateral load. Both CS3 and CS4 have reduced much in the deflection and wall moment, but the moment of inertia of both cases do not have high value. Thus moment of inertia does not have big impact in resisting the lateral deflection.

For human comfort criteria, all case studies meet the human perception level where both along-wind and cross-wind acceleration fall under range 1. The accelerations are more than $0.05 m/s^2$ hence, the occupants of the structure do not perceive any motion of the building when it sways.

In a nutshell, the objectives of the project have been achieved. The current practice of structural system of tall buildings and also the significance of service core in tall buildings have been discussed. The wind condition in Malaysia is in mild condition hence the basic wind speed used for the wind loading calculation is within the range, which is 15m/s. The analysis shows that different orientation of core will have different impact on lateral stiffness of structure. The dynamic response of structures is checked for human comfort and the results show that the structures are within human perception level. Finally an optimum structure has been proposed in this project.

5.2 Recommendation

Although the objectives of this project have been achieved, there are some recommendations to improve the analysis of the behavior of the case studies. In the wind loading calculations, Standard Method has been adopted in calculating wind forces in the context of British Standard. Standard Method will give more conservative value and the calculations can be performed manually. In order to have a more precise and accurate wind forces, it can be determined through the usage of certain software to perform calculation based on Directional Method.

In measuring the human comfort criteria, both along-wind and cross-wind accelerations are considered. Although it has not yet proved possible to develop a corresponding technique for the along-wind and cross-wind responses, empirical formulas are available to allow a rough estimate of the accelerations. Nonetheless, a more accurate method is to test an aero-elastic model in a wind tunnel.

For this project, the structural models are subjected to wind load in one direction, which is Y-direction. In real life situation, wind blows in any direction. Hence, the project may be studied for wind loaded structures in various directions so that more analysis results can be reviewed and discussed.

This project is limited to research stage at the moment. In order to enhance the findings so that they can be an extra reference for the people from the industry (construction or consultant line), cost impact of different location of service core can be carried out as well.

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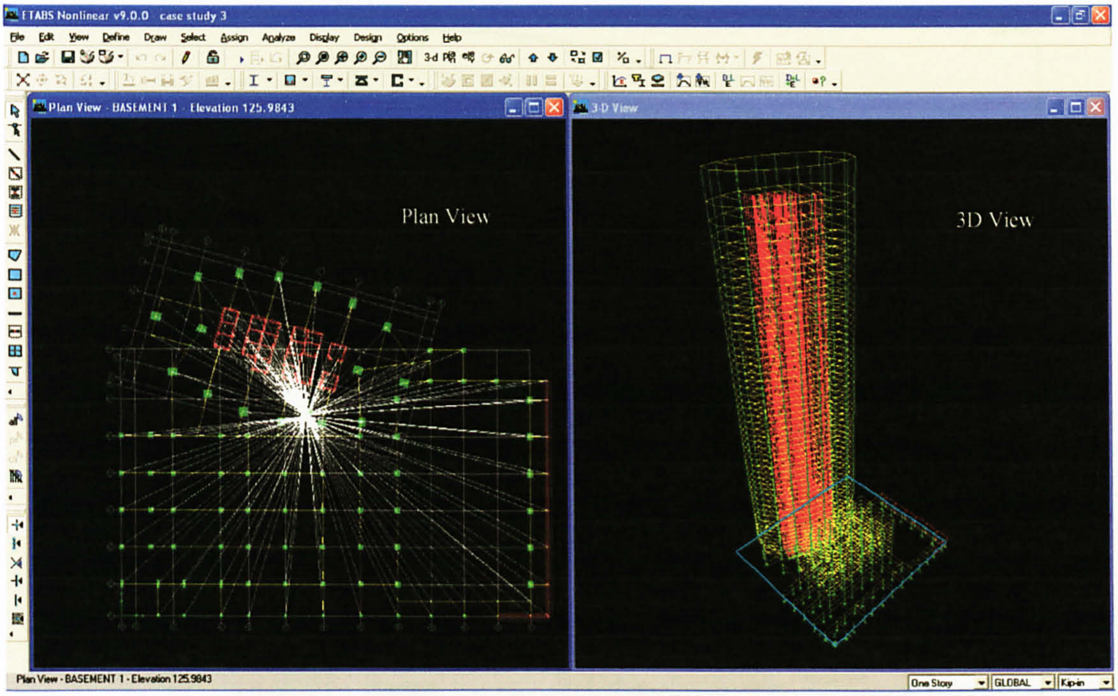
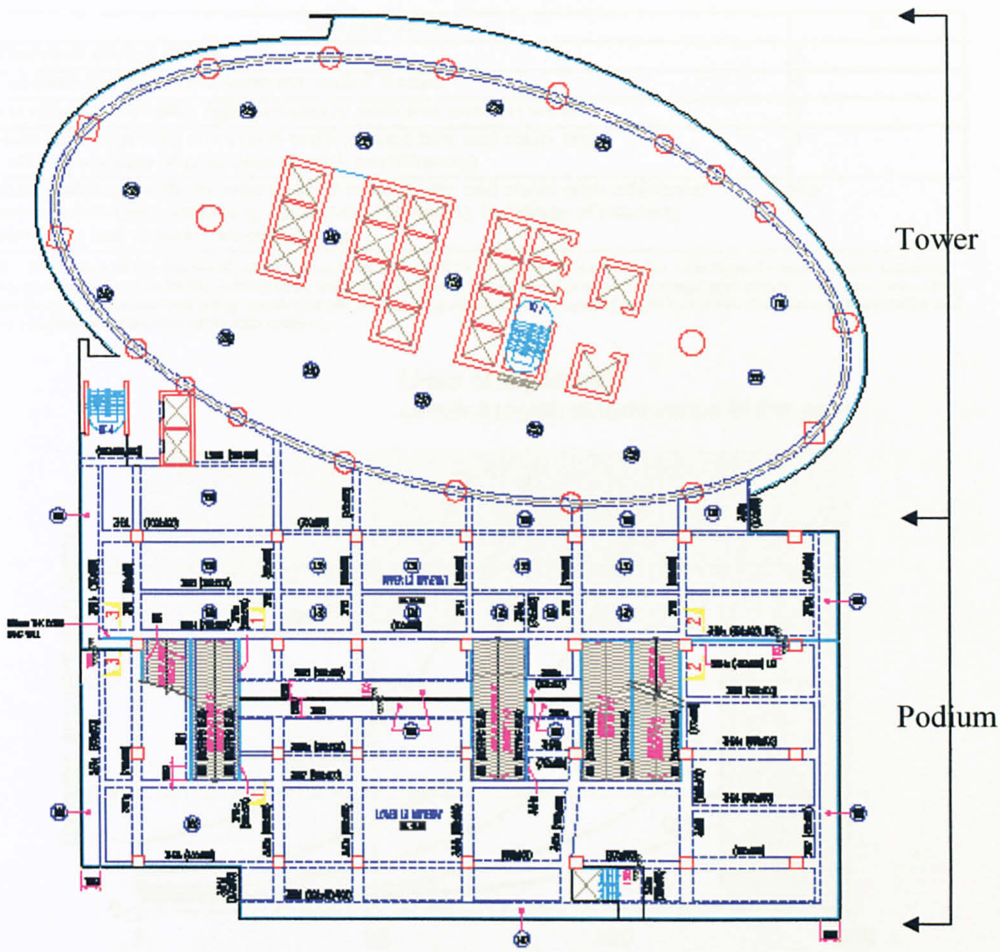
APPENDICES

APPENDIX A

ETABS STRUCTURAL MODEL



APPENDIX B
GEOMETRIC SHAPE OF CASE STUDY



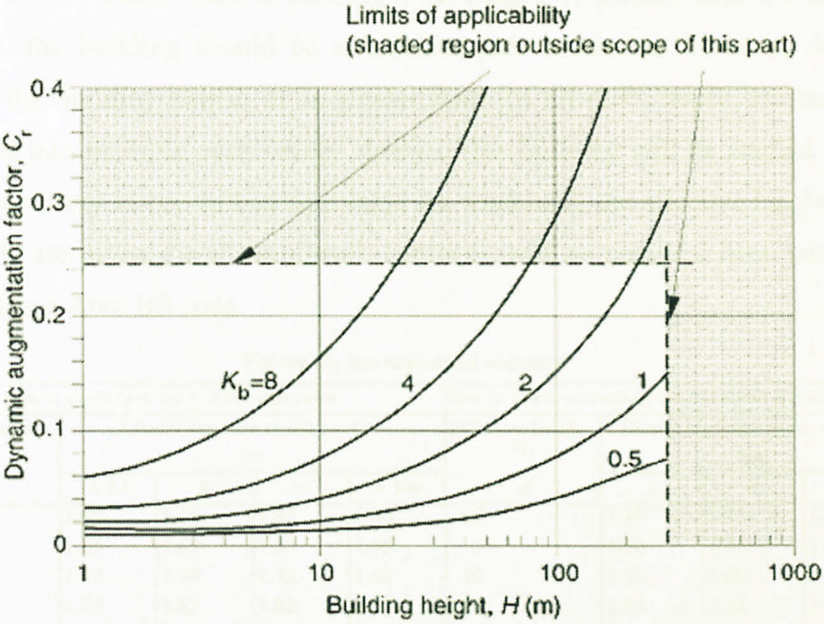
APPENDIX C

WIND LOADING: STANDARD METHOD

Building-type factor K_b

Type of building	K_b
Welded steel unclad flames	8
Bolted steel and reinforced concrete unclad frames	4
Portal sheds and similar light structures with few internal walls	2
Framed buildings with structural walls around lifts and stairs only (e.g. office buildings of open plan or with partitioning)	1
Framed buildings with structural walls around lifts and stairs with additional masonry subdivision walls (e.g. apartment buildings), buildings of masonry construction and timber-framed housing	0.5

NOTE The values of the factors K_b and C_r have been derived for typical building structures with typical frequency and damping characteristics, under typical UK wind speeds, without accounting for topography or terrain roughness effects. More accurate values of these factors may be derived using Annex C when the building characteristics are not typical, or when the effects of topography and terrain roughness need to be taken into account.



Dynamic augmentation factor C_r

<u>Basic Wind Speed & Site Wind Speed</u>

Basic wind speed, V_b at Kuala Lumpur will be determined for this project because the case study is located at Kuala Lumpur city centre. Site wind speed, V_s will be calculated based on certain factors including altitude factor S_a, direction factor S_d, seasonal factor S_s, and probability factor S_p. The formula is shown below:

$$V_s = V_b \times S_a \times S_d \times S_s \times S_p$$

Altitude factor is dependant on the significance of topography to be considered so that to adjust the basic wind speeds for the altitude of the building site above sea level. Then the direction factor is dependant on the orientation of the building while probability factor may be used to count on the probability of the risk of the basic wind speed to be exceeded from standard value Q = 0.02 annually. In this project, the seasonal factor is not included because all buildings in Kuala Lumpur are exposed to the same condition of wind throughout the year.

Effective Wind Speed

Effective wind speed, V_e is calculated based on the formula below:

$$V_e = V_s \times S_b$$

V_s is the site wind speed and S_b is the terrain and building factor. The factor S_b is dependant on the effective height H_e of the building which will be exposed to wind force and also the location of building site either in country or in town. According to BS 6399-2-1997 code, when a building with height, H greater than the crosswind breath, B, the building should be subdivided into a number of parts. As in the research, the building height, H is greater than 2B (H>2B), hence the building is subdivided into multiple parts (every storey of the building will be studied for wind load). Since every storey will be calculated for wind load, the effective height, H_e will be equal to storey height of each level. Factor S_b will be obtained from table below which is taken from BS code.

Factor S_b for standard method

Site in country or up to 2 km into town					Site in town, extending ≥ 2 km upwind from the site			
Effective height H_e	Closest distance to sea upwind km				Effective height H_e	Closest distance to sea upwind km		
m	≤ 0.1	2	10	≥ 100	m	2	10	≥ 100
≤ 2	1.48	1.40	1.35	1.26	≤ 2	1.18	1.15	1.07
5	1.65	1.62	1.57	1.45	5	1.50	1.45	1.36
10	1.78	1.78	1.73	1.62	10	1.73	1.69	1.58
15	1.85	1.85	1.82	1.71	15	1.85	1.82	1.71
20	1.90	1.90	1.89	1.77	20	1.90	1.89	1.77
30	1.96	1.96	1.96	1.85	30	1.96	1.96	1.85
50	2.04	2.04	2.04	1.95	50	2.04	2.04	1.95
100	2.12	2.12	2.12	2.07	100	2.12	2.12	2.07

NOTE 1 Interpolation may be used within each table.
NOTE 2 The figures in this table have been derived from reference [5].
NOTE 3 Values assume a diagonal dimension a = 5 m.
NOTE 4 If H_e > 100 m use the directional method of Section 3.

Dynamic Pressure & Surface Pressure

Dynamic pressure, q_s is calculated based on the formula shown below:

$$q_s = 0.613 V_e^2$$

Effective wind speed, V_e will be converted into an equivalent dynamic pressure. Then surface pressure will be divided into two parts including external surface pressure and internal surface pressure.

- External surface pressure is as follow:

$$p_e = q_s C_{pe} C_a$$

- Internal Surface Pressure is as follow:

$$p_i = q_s C_{pi} C_a$$

C_{pe}, C_{pi}, and C_a are the standard pressure coefficient that are dependant on the shape and form of the building. For the factor C_{pe}, two different building plans are used (rectangular-plan and circular-plan buildings) in determining the value because the case study building shape is a combination of rectangular and eclipse plans. Below are the tables for external pressure.

External pressure coefficients C_{pe} for vertical walls

Vertical wall face	Span ratio of building		Vertical wall face		Exposure case	
	$D/H \leq 1$	$D/H \geq 4$			Isolated	Funnelling
Windward (front)	+0.85	+0.6	Side	Zone A	−1.3	−1.6
Leeward (rear)	−0.5	−0.5		Zone B	−0.8	−0.9
				Zone C	−0.5	−0.9

NOTE Interpolation may be used in the range $1 < D/H < 4$. See 2.4.1.4 for interpolation between isolated and funnelling.

External pressure coefficients C_{pe} for walls of circular-plan buildings

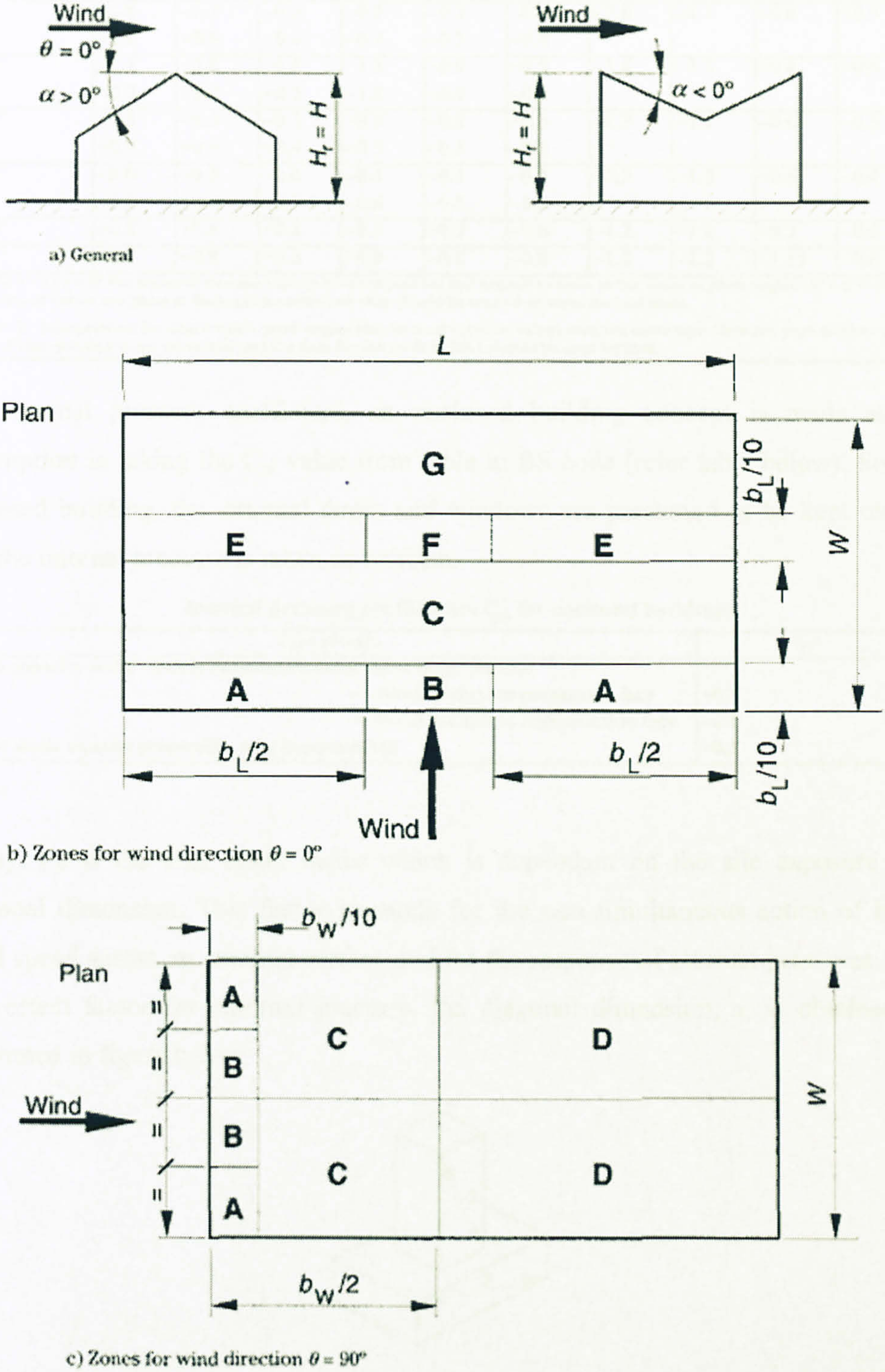
Position on periphery	Surface rough or with projections		Surface smooth	
θ	$H/d \geq 10$	$H/d \leq 2.5$	$H/d \geq 10$	$H/d \leq 2.5$
0°	+1.0	+1.0	+1.0	+1.0
10°	+0.9	+0.9	+0.9	+0.9
20°	+0.7	+0.7	+0.7	+0.7
30°	+0.4	+0.4	+0.35	+0.35
40°	0	0	0	0
50°	−0.5	−0.4	−0.7	−0.5
60°	−0.95	−0.8	−1.2	−1.05
70°	−1.25	−1.1	−1.4	−1.25
80°	−1.2	−1.05	−1.45	−1.3
90°	−1.0	−0.85	−1.4	−1.2
100°	−0.8	−0.65	−1.1	−0.85
120°	−0.5	−0.35	−0.6	−0.4
140°	−0.4	−0.3	−0.35	−0.25
160°	−0.4	−0.3	−0.35	−0.25
180°	−0.4	−0.3	−0.35	−0.25

NOTE 1 Interpolation may be used in the range $2.5 < H/d < 10$.

NOTE 2 Valid for diameters greater than $d = 1$ m.

NOTE 3 The position on the periphery at $\theta = 40°$ where $C_{pe} = 0$ is a region where the pressure will change rapidly with time, due to fluctuations in wind direction caused by atmospheric turbulence, over the range $C_{pe} = \pm 0.7$. It is therefore the region with the highest risk of fatigue damage to cladding fixings.

Besides, the wind load subjected to roof is considered separately. Inside the BS code, there are several tables to choose from to get the C_{pe} value based on the shape of the roof. As in this case study, duopitch roof is used. Thus, the external pressure coefficient for duopitch roof will be obtained in another table shown below.



Key for duopitch roofs

External pressure coefficients C_{pe} for duopitch roofs of buildings

Pitch angle α	Zone for $\theta = 0^{\circ}$						Zone for $\theta = 90^{\circ}$			
	A	B	C	E	F	G	A	B	C	D
−45°	−0.9	−0.8	−0.9	−1.1	−0.7	−0.7	−1.5	−1.3	−1.0	−0.9
−30°	−1.7	−1.0	−0.9	−0.8	−0.7	−0.7	−1.7	−1.3	−1.0	−0.8
−15°	−2.6	−1.0	−0.9	−0.7	−0.5	−0.5	−2.6	−1.4	−0.8	−0.8
−5°	−2.4	−1.2	−0.8	−0.5	−0.3	−0.5	−2.2	−1.5	−0.7	−0.7
+5°	−1.8 +0.0	−1.2 +0.0	−0.6 +0.0	−0.9 −0.9	−0.3 −0.3	−0.4 −0.4	−2.0	−1.1	−0.6	−0.5
+15°	−1.1 +0.2	−0.8 +0.2	−0.4 +0.2	−1.3 −1.3	−0.9 −0.9	−0.5 −0.5	−1.6	−1.5	−0.6	−0.4
+30°	−0.5 +0.8	−0.5 +0.5	−0.2 +0.4	−0.9 −0.9	−0.5 −0.5	−0.5 −0.5	−1.2	−1.1	−0.6	−0.5
+45°	−0.0 +0.8	−0.0 +0.6	−0.0 +0.7	−0.4 −0.4	−0.3 −0.3	−0.3 −0.3	−1.2	−1.2	−0.6	−0.4
+60°	+0.8	+0.8	+0.8	−0.8	−0.7	−0.6	−1.2	−1.2	−0.7	−0.6
+75°	+0.8	+0.8	+0.8	−0.9	−0.6	−0.8	−1.2	−1.2	−1.15	−0.6

NOTE 1 At $\theta = 0^{\circ}$ the pressure changes rapidly between positive and negative values in the range of pitch angles $+5^{\circ} < \alpha < +45^{\circ}$. Two sets of values are given at these pitch angles and they should be treated as separate load cases.

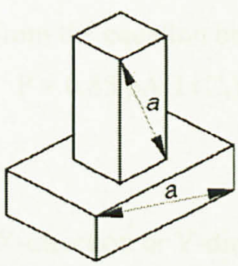
NOTE 2 Interpolation for intermediate pitch angles may be used between values with the same sign. Between pitch angles +5° and −5° interpolation is not permitted and the data for flat roofs in 2.5.1 should be used instead.

For internal pressure coefficient, an enclosed building concept is made as an assumption in taking the C_{pi} value from table in BS code (refer table below). For an enclosed building, the external doors and windows are presumed to be kept closed and the internal pressure is taken as uniform.

Internal pressure coefficients C_{pi} for enclosed buildings

Type of walls	C_{pi}
Two opposite walls equally permeable; other faces impermeable	
— Wind normal to permeable face	+0.2
— Wind normal to impermeable face	−0.3
Four walls equally permeable; roof impermeable	−0.3

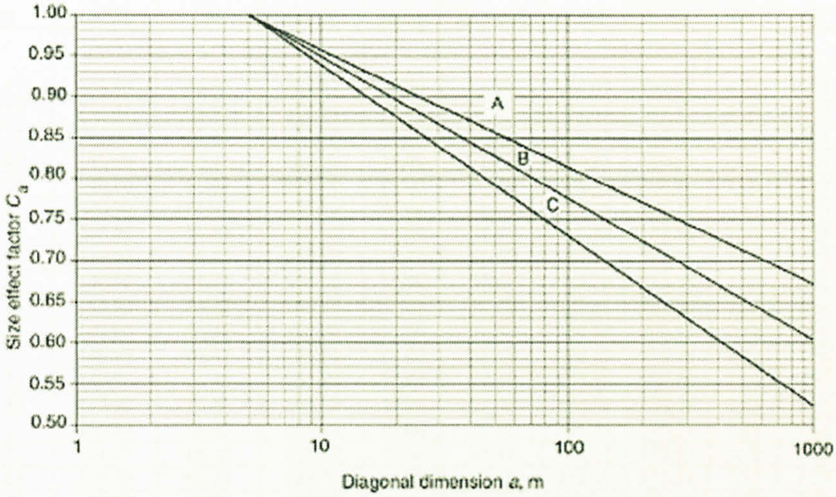
Lastly, C_a is the size effect factor which is dependant on the site exposure and diagonal dimension. This factor accounts for the non-simultaneous action of basic wind speed across an external surface and for the response of internal pressures. The size effect factor for external pressure, the diagonal dimension, a, is obtained as illustrated in figure below.



Oh the other hand, the relevant diagonal dimension, a, for the internal pressure may be calculated as the formula below:

$$a = 10 \times \sqrt[3]{\text{internal volume of storey}}$$

With this information, the factor C_a value can be obtained from table and graph as shown below.



Key to lines on Figure 4							
Effective height H_e	Site in country: closest distance to sea (km)				Site in town: closest distance to sea (km)		
m	0 to < 2	2 to < 10	10 to < 100	≥ 100	2 to < 10	10 to < 100	≥ 100
≤ 2	A	B	B	B	C	C	C
> 2 to 5	A	B	B	B	C	C	C
> 5 to 10	A	A	B	B	A	C	C
> 10 to 15	A	A	B	B	A	B	B
> 15 to 20	A	A	B	B	A	B	B
> 20 to 30	A	A	A	B	A	A	B
> 30 to 50	A	A	A	B	A	A	B
> 50	A	A	A	B	A	A	B

Size effect factor C_a of standard method

Hence, the net surface pressure will be obtained as the formula below:

$$p = p_e - p_i$$

<u>Wind Load at Each Storey</u>

The wind load will be obtained from the equation below:

$$P = 0.85\ pA(1+C_r)$$

where

p is the net surface pressure

A is the projected area either in X-direction or Y-direction

C_r is the Dynamic Augmentation

APPENDIX D

WIND LOADING CALCULATION

Storey Label	Storey Height Below (m)	Projected Width X-Direction (m)	Projected Area X-Direction (m^2)	Projected Width Y-Direction (m)	Projected Area Y-Direction (m^2)	Site Wind Speed Vs (m/s)	Effective Wind Speed Ve (m/s)	Net Surface Pressure, p (N/m^2)				Wind Load, P(kN)	
								Front		Rear		X-Dir	Y-Dir
								X-dir	Y-dir	X-dir	Y-dir		
Lift motor room	7.00	35.23	246.58	66.42	464.97	15.00	31.99	592.97	592.97	4.71	4.71	139.32	262.72
50	6.00	35.23	211.35	66.42	398.54	15.00	31.93	591.57	591.57	5.63	5.63	118.95	224.30
49	6.50	35.23	228.96	66.42	431.76	15.00	31.88	589.57	589.57	5.61	5.61	128.43	242.17
48	4.00	35.23	140.90	66.42	265.70	15.00	31.82	589.83	589.83	8.01	8.01	78.74	148.48
47	4.00	35.23	140.90	66.42	265.70	15.00	31.78	588.50	588.50	7.99	7.99	78.56	148.15
46	4.00	35.23	140.90	66.42	265.70	15.00	31.75	587.17	587.17	7.97	7.97	78.39	147.81
45	4.00	35.23	140.90	66.42	265.70	15.00	31.71	585.84	585.84	7.95	7.95	78.21	147.48
44	4.00	35.23	140.90	66.42	265.70	15.00	31.67	584.51	584.51	7.93	7.93	78.03	147.14
43	4.00	35.23	140.90	66.42	265.70	15.00	31.64	583.18	583.18	7.92	7.92	77.85	146.81
42	4.00	35.23	140.90	66.42	265.70	15.00	31.60	581.85	581.85	7.90	7.90	77.68	146.47
41	4.00	35.23	140.90	66.42	265.70	15.00	31.57	580.53	580.53	7.88	7.88	77.50	146.14
40	4.00	35.23	140.90	66.42	265.70	15.00	31.53	579.20	579.20	7.86	7.86	77.32	145.81
39	4.00	35.23	140.90	66.42	265.70	15.00	31.49	577.88	577.88	7.84	7.84	77.15	145.47
38	4.00	35.23	140.90	66.42	265.70	15.00	31.46	576.56	576.56	7.83	7.83	76.97	145.14
37	4.00	35.23	140.90	66.42	265.70	15.00	31.42	575.24	575.24	7.81	7.81	76.79	144.81
36	4.30	35.23	151.47	66.42	285.62	15.00	31.39	573.93	573.93	7.79	7.79	82.36	155.31
35	4.00	35.23	140.90	66.42	265.70	15.00	31.35	572.51	572.51	7.77	7.77	76.43	144.12
34	4.00	35.23	140.90	66.42	265.70	15.00	31.31	571.20	571.20	7.75	7.75	76.25	143.79
33	4.00	35.23	140.90	66.42	265.70	15.00	31.28	569.88	569.88	7.74	7.74	76.08	143.46
32	4.00	35.23	140.90	66.42	265.70	15.00	31.24	568.57	568.57	7.72	7.72	75.90	143.13
31	4.00	35.23	140.90	66.42	265.70	15.00	31.20	567.26	567.26	7.70	7.70	75.73	142.80
30	4.00	35.23	140.90	66.42	265.70	15.00	31.17	565.96	565.96	7.68	7.68	75.55	142.47
29	4.00	35.23	140.90	66.42	265.70	15.00	31.13	564.65	564.65	7.66	7.66	75.38	142.14
28	4.00	35.23	140.90	66.42	265.70	15.00	31.10	563.34	563.34	7.65	7.65	75.20	141.81
27	4.00	35.23	140.90	66.42	265.70	15.00	31.06	562.04	562.04	7.63	7.63	75.03	141.49
26	4.00	35.23	140.90	66.42	265.70	15.00	30.95	557.91	557.91	7.57	7.57	74.48	140.45
25	4.00	35.23	140.90	66.42	265.70	15.00	30.80	552.73	552.73	7.50	7.50	73.79	139.14
24	4.00	35.23	140.90	66.42	265.70	15.00	30.66	547.57	547.57	7.43	7.43	73.10	137.84
23	4.00	35.23	140.90	66.42	265.70	15.00	30.51	542.44	542.44	7.36	7.36	72.41	136.55
22	4.00	35.23	140.90	66.42	265.70	15.00	30.37	537.33	537.33	7.29	7.29	71.73	135.27
21	4.00	35.23	140.90	66.42	265.70	15.00	30.23	532.25	532.25	7.22	7.22	71.05	133.99
20	4.00	35.23	140.90	66.42	265.70	15.00	30.08	527.19	527.19	7.16	7.16	70.38	132.71
19	4.30	35.23	151.47	66.42	285.62	15.00	29.94	522.16	522.16	7.09	7.09	74.93	141.30
18	4.00	35.23	140.90	66.42	265.70	15.00	29.78	516.93	516.93	7.18	7.18	68.99	130.09
17	4.00	35.23	140.90	66.42	265.70	15.00	29.64	511.95	511.95	7.11	7.11	68.32	128.84
16	4.00	35.23	140.90	66.42	265.70	15.00	29.49	506.98	506.98	7.04	7.04	67.66	127.59
15	4.00	35.23	140.90	66.42	265.70	15.00	29.35	502.05	502.05	6.97	6.97	67.00	126.34
14	4.00	35.23	140.90	66.42	265.70	15.00	29.16	495.54	495.54	6.88	6.88	66.13	124.71
13	4.00	35.23	140.90	66.42	265.70	15.00	28.86	485.40	485.40	6.74	6.74	64.78	122.15
12	4.90	35.23	172.60	66.42	325.48	15.00	28.56	474.76	474.76	6.00	6.00	77.71	146.54
11	4.90	35.23	172.60	66.42	325.48	15.00	28.19	462.62	462.62	5.85	5.85	75.73	142.80
10	3.40	73.48	249.85	66.42	225.84	15.00	27.83	306.12	306.12	-85.4	-85.4	93.96	84.93
9	3.00	73.48	220.45	66.42	199.27	15.00	27.46	299.57	299.57	-81.8	-81.8	80.76	73.00
8	3.00	73.48	220.45	66.42	199.27	15.00	27.10	291.77	291.77	-79.7	-79.7	78.66	71.10
7	3.00	73.48	220.45	66.42	199.27	15.00	26.74	284.07	284.07	-77.6	-77.6	76.58	69.22
6	3.00	73.48	220.45	66.42	199.27	15.00	26.30	274.71	274.71	-75.0	-75.0	74.06	66.94
5	3.00	73.48	220.45	66.42	199.27	15.00	25.76	263.55	263.55	-72.0	-72.0	71.05	64.22
4	3.00	73.48	220.45	66.42	199.27	15.00	24.71	242.62	242.62	-66.3	-66.3	65.41	59.12
3	5.10	73.48	374.77	103.84	529.56	15.00	23.44	212.11	212.11	-58.3	-58.3	97.32	137.52
2	4.50	73.48	330.68	103.84	467.26	15.00	19.68	149.85	149.85	-40.7	-40.7	60.52	85.52
1	0.00	0.00	0.00	0.00	0.00	15.00	16.05	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX E

LATERAL STIFFNESS CHECK

Original Case

Story	Height (m)	UX (m)	UY (m)	dx (m)	dy (m)	Delta (m)	H/delta
LIFT ROOM	7	0.026	0.217	0.001	0.009	0.009	809
L50	6	0.025	0.208	0.001	0.007	0.007	805
L49	6.5	0.024	0.201	0.001	0.008	0.008	798
L48	4	0.023	0.193	0.001	0.005	0.005	794
L47	4	0.022	0.188	0.001	0.005	0.005	796
L46	4	0.022	0.183	0.001	0.005	0.005	794
L45	4	0.021	0.178	0.001	0.005	0.005	794
L44	4	0.021	0.173	0.001	0.005	0.005	794
L43	4	0.020	0.168	0.001	0.005	0.005	794
L42	4	0.019	0.163	0.001	0.005	0.005	779
L41	4	0.019	0.158	0.001	0.005	0.005	779
L40	4	0.018	0.153	0.001	0.005	0.005	794
L39	4	0.018	0.148	0.001	0.005	0.005	779
L38	4	0.017	0.143	0.001	0.005	0.005	779
L37	4	0.016	0.138	0.001	0.005	0.005	779
L36	4.3	0.016	0.132	0.001	0.005	0.005	835
L35	4	0.015	0.127	0.001	0.005	0.006	723
L34	4	0.014	0.122	0.001	0.005	0.005	777
L33	4	0.014	0.117	0.001	0.005	0.005	779
L32	4	0.013	0.112	0.001	0.005	0.005	777
L31	4	0.012	0.107	0.001	0.005	0.005	779
L30	4	0.012	0.101	0.001	0.005	0.005	794
L29	4	0.011	0.096	0.001	0.005	0.005	792
L28	4	0.011	0.091	0.001	0.005	0.005	794
L27	4	0.010	0.086	0.001	0.005	0.005	792
L26	4	0.009	0.081	0.001	0.005	0.005	827
L25	4	0.009	0.077	0.001	0.005	0.005	810
L24	4	0.008	0.072	0.001	0.005	0.005	844
L23	4	0.007	0.067	0.001	0.005	0.005	844
L22	4	0.007	0.062	0.001	0.005	0.005	862
L21	4	0.006	0.058	0.001	0.005	0.005	881
L20	4	0.006	0.053	0.001	0.004	0.004	901
L19	4.3	0.005	0.049	0.001	0.005	0.005	927
L18	4	0.004	0.044	0.001	0.004	0.004	946
L17	4	0.004	0.040	0.001	0.004	0.004	992
L16	4	0.003	0.036	0.000	0.004	0.004	1047
L15	4	0.003	0.032	0.000	0.004	0.004	1075
L14	4	0.003	0.029	0.000	0.004	0.004	1135
L13	4	0.002	0.025	0.000	0.003	0.003	1172
L12	4.9	0.002	0.022	0.000	0.004	0.004	1320
L11	4.9	0.002	0.018	0.001	0.004	0.004	1348
L10	3.4	0.001	0.014	0.000	0.002	0.002	1539
L9	3	0.001	0.012	0.000	0.002	0.002	1664
L8	3	0.001	0.010	0.000	0.002	0.002	1871
L7	3	0.001	0.009	0.000	0.002	0.002	1871
L6	3	0.001	0.007	0.000	0.001	0.001	2137
L5	3	0.001	0.006	0.000	0.001	0.001	2301
L4	3	0.000	0.004	0.000	0.001	0.001	2716
L3	5.1	0.000	0.003	0.000	0.002	0.002	3163
L2	4.5	0.000	0.002	0.000	0.001	0.001	4500
L1	4.5	0.000	0.001	0.000	0.001	0.001	7398
BASEMENT1	3.2	0.000	0.000	0.000	0.000	0.000	32000

Case 1 (CS1)

Story	Height (m)	UX (m)	UY (m)	dx (m)	dy (m)	Delta (m)	H/delta
LIFT ROOM	7	0.022	0.216	0.001	0.009	0.009	801
L50	6	0.021	0.208	0.001	0.007	0.008	797
L49	6.5	0.021	0.200	0.001	0.008	0.008	799
L48	4	0.020	0.192	0.001	0.005	0.005	796
L47	4	0.019	0.187	0.001	0.005	0.005	796
L46	4	0.019	0.182	0.001	0.005	0.005	781
L45	4	0.018	0.177	0.001	0.005	0.005	796
L44	4	0.018	0.172	0.001	0.005	0.005	796
L43	4	0.017	0.167	0.001	0.005	0.005	781
L42	4	0.017	0.162	0.001	0.005	0.005	779
L41	4	0.016	0.157	0.000	0.005	0.005	781
L40	4	0.016	0.152	0.001	0.005	0.005	781
L39	4	0.015	0.146	0.001	0.005	0.005	794
L38	4	0.015	0.141	0.000	0.005	0.005	781
L37	4	0.014	0.136	0.001	0.005	0.005	766
L36	4.3	0.014	0.131	0.001	0.005	0.005	837
L35	4	0.013	0.126	0.001	0.005	0.005	736
L34	4	0.013	0.121	0.001	0.005	0.005	781
L33	4	0.012	0.116	0.001	0.005	0.005	779
L32	4	0.011	0.110	0.001	0.005	0.005	781
L31	4	0.011	0.105	0.001	0.005	0.005	794
L30	4	0.010	0.100	0.001	0.005	0.005	794
L29	4	0.010	0.095	0.001	0.005	0.005	796
L28	4	0.009	0.090	0.001	0.005	0.005	810
L27	4	0.009	0.085	0.001	0.005	0.005	810
L26	4	0.008	0.081	0.001	0.005	0.005	829
L25	4	0.008	0.076	0.001	0.005	0.005	827
L24	4	0.007	0.071	0.001	0.005	0.005	846
L23	4	0.006	0.066	0.001	0.005	0.005	864
L22	4	0.006	0.062	0.001	0.005	0.005	862
L21	4	0.005	0.057	0.001	0.004	0.004	903
L20	4	0.005	0.053	0.001	0.004	0.004	903
L19	4.3	0.004	0.048	0.001	0.005	0.005	950
L18	4	0.004	0.044	0.000	0.004	0.004	971
L17	4	0.003	0.040	0.000	0.004	0.004	995
L16	4	0.003	0.036	0.000	0.004	0.004	1047
L15	4	0.003	0.032	0.000	0.004	0.004	1104
L14	4	0.002	0.028	0.000	0.004	0.004	1139
L13	4	0.002	0.025	0.000	0.003	0.003	1207
L12	4.9	0.002	0.021	0.000	0.004	0.004	1320
L11	4.9	0.001	0.018	0.000	0.004	0.004	1395
L10	3.4	0.001	0.014	0.000	0.002	0.002	1617
L9	3	0.001	0.012	0.000	0.002	0.002	1656
L8	3	0.001	0.010	0.000	0.002	0.002	1762
L7	3	0.001	0.009	0.000	0.002	0.002	1996
L6	3	0.001	0.007	0.000	0.001	0.001	2137
L5	3	0.000	0.006	0.000	0.001	0.001	2301
L4	3	0.000	0.004	0.000	0.001	0.001	2716
L3	5.1	0.000	0.003	0.000	0.002	0.002	3181
L2	4.5	0.000	0.002	0.000	0.001	0.001	4500
L1	4.5	0.000	0.001	0.000	0.001	0.001	7398
BASEMENT1	3.2	0.000	0.000	0.000	0.000	0.000	32000

Case 2 (CS2)

Story	Height (m)	UX (m)	UY (m)	dx (m)	dy (m)	Delta (m)	H/delta
LIFT ROOM	7	0.024	0.204	0.001	0.008	0.008	871
L50	6	0.023	0.196	0.001	0.007	0.007	864
L49	6.5	0.023	0.190	0.001	0.008	0.008	862
L48	4	0.022	0.182	0.001	0.005	0.005	846
L47	4	0.021	0.177	0.001	0.005	0.005	864
L46	4	0.021	0.173	0.001	0.005	0.005	846
L45	4	0.020	0.168	0.000	0.005	0.005	864
L44	4	0.020	0.163	0.001	0.005	0.005	844
L43	4	0.019	0.159	0.000	0.005	0.005	846
L42	4	0.019	0.154	0.001	0.005	0.005	829
L41	4	0.018	0.149	0.001	0.005	0.005	844
L40	4	0.018	0.145	0.001	0.005	0.005	829
L39	4	0.017	0.140	0.001	0.005	0.005	844
L38	4	0.017	0.135	0.001	0.005	0.005	827
L37	4	0.016	0.130	0.001	0.005	0.005	829
L36	4.3	0.015	0.125	0.001	0.005	0.005	889
L35	4	0.015	0.121	0.001	0.005	0.005	777
L34	4	0.014	0.116	0.001	0.005	0.005	827
L33	4	0.014	0.111	0.001	0.005	0.005	827
L32	4	0.013	0.106	0.001	0.005	0.005	827
L31	4	0.012	0.101	0.001	0.005	0.005	827
L30	4	0.012	0.096	0.001	0.005	0.005	827
L29	4	0.011	0.092	0.001	0.005	0.005	844
L28	4	0.011	0.087	0.001	0.005	0.005	844
L27	4	0.010	0.082	0.001	0.005	0.005	862
L26	4	0.009	0.078	0.001	0.005	0.005	842
L25	4	0.009	0.073	0.001	0.005	0.005	881
L24	4	0.008	0.068	0.001	0.005	0.005	881
L23	4	0.007	0.064	0.001	0.005	0.005	881
L22	4	0.007	0.059	0.001	0.004	0.004	921
L21	4	0.006	0.055	0.001	0.004	0.004	924
L20	4	0.006	0.051	0.001	0.004	0.004	943
L19	4.3	0.005	0.047	0.001	0.004	0.004	968
L18	4	0.005	0.042	0.001	0.004	0.004	1017
L17	4	0.004	0.038	0.001	0.004	0.004	1044
L16	4	0.004	0.034	0.000	0.004	0.004	1075
L15	4	0.003	0.031	0.001	0.004	0.004	1131
L14	4	0.003	0.027	0.000	0.003	0.003	1168
L13	4	0.002	0.024	0.000	0.003	0.003	1284
L12	4.9	0.002	0.021	0.000	0.004	0.004	1320
L11	4.9	0.002	0.017	0.000	0.003	0.003	1474
L10	3.4	0.001	0.014	0.000	0.002	0.002	1603
L9	3	0.001	0.012	0.000	0.002	0.002	1762
L8	3	0.001	0.010	0.000	0.002	0.002	1871
L7	3	0.001	0.008	0.000	0.002	0.002	1982
L6	3	0.001	0.007	0.000	0.001	0.001	2137
L5	3	0.000	0.005	0.000	0.001	0.001	2491
L4	3	0.000	0.004	0.000	0.001	0.001	2716
L3	5.1	0.000	0.003	0.000	0.002	0.002	3392
L2	4.5	0.000	0.002	0.000	0.001	0.001	4478
L1	4.5	0.000	0.001	0.000	0.001	0.001	9000
BASEMENT1	3.2	0.000	0.000	0.000	0.000	0.000	32000

Case 3 (CS3)

Story	Height (m)	UX (m)	UY (m)	dx (m)	dy (m)	Delta (m)	H/delta
LIFT ROOM	7	0.024	0.189	0.001	0.007	0.007	939
L50	6	0.023	0.181	0.001	0.006	0.006	945
L49	6.5	0.022	0.175	0.001	0.007	0.007	949
L48	4	0.021	0.168	0.001	0.004	0.004	924
L47	4	0.021	0.164	0.001	0.004	0.004	946
L46	4	0.020	0.160	0.001	0.004	0.004	924
L45	4	0.020	0.156	0.001	0.004	0.004	946
L44	4	0.019	0.151	0.001	0.004	0.004	921
L43	4	0.019	0.147	0.001	0.004	0.004	924
L42	4	0.018	0.143	0.001	0.004	0.004	921
L41	4	0.017	0.138	0.001	0.004	0.004	903
L40	4	0.017	0.134	0.001	0.004	0.004	921
L39	4	0.016	0.130	0.000	0.004	0.004	903
L38	4	0.016	0.125	0.001	0.004	0.004	901
L37	4	0.015	0.121	0.001	0.004	0.004	901
L36	4.3	0.015	0.117	0.001	0.004	0.004	971
L35	4	0.014	0.112	0.001	0.005	0.005	842
L34	4	0.013	0.107	0.001	0.004	0.004	901
L33	4	0.013	0.103	0.001	0.004	0.004	901
L32	4	0.012	0.099	0.001	0.004	0.005	881
L31	4	0.012	0.094	0.000	0.004	0.004	903
L30	4	0.011	0.090	0.001	0.004	0.004	921
L29	4	0.011	0.085	0.001	0.004	0.004	901
L28	4	0.010	0.081	0.001	0.004	0.004	921
L27	4	0.009	0.077	0.001	0.004	0.004	921
L26	4	0.009	0.072	0.001	0.004	0.004	921
L25	4	0.008	0.068	0.001	0.004	0.004	943
L24	4	0.008	0.064	0.001	0.004	0.004	943
L23	4	0.007	0.060	0.001	0.004	0.004	965
L22	4	0.006	0.056	0.001	0.004	0.004	965
L21	4	0.006	0.052	0.001	0.004	0.004	992
L20	4	0.005	0.048	0.001	0.004	0.004	1040
L19	4.3	0.005	0.044	0.001	0.004	0.004	1041
L18	4	0.004	0.040	0.001	0.004	0.004	1071
L17	4	0.004	0.036	0.001	0.004	0.004	1131
L16	4	0.003	0.032	0.000	0.004	0.004	1135
L15	4	0.003	0.029	0.000	0.003	0.003	1203
L14	4	0.002	0.026	0.000	0.003	0.003	1284
L13	4	0.002	0.023	0.000	0.003	0.003	1327
L12	4.9	0.002	0.020	0.000	0.003	0.003	1436
L11	4.9	0.001	0.016	0.000	0.003	0.003	1568
L10	3.4	0.001	0.013	0.000	0.002	0.002	1692
L9	3	0.001	0.011	0.000	0.002	0.002	1871
L8	3	0.001	0.009	0.000	0.002	0.002	1996
L7	3	0.001	0.008	0.000	0.001	0.001	2137
L6	3	0.001	0.007	0.000	0.001	0.001	2301
L5	3	0.000	0.005	0.000	0.001	0.001	2491
L4	3	0.000	0.004	0.000	0.001	0.001	3000
L3	5.1	0.000	0.003	0.000	0.002	0.002	3370
L2	4.5	0.000	0.002	0.000	0.001	0.001	5000
L1	4.5	0.000	0.001	0.000	0.001	0.001	8825
BASEMENT1	3.2	0.000	0.000	0.000	0.000	0.000	32000

Case 4 (CS4)

Story	Height (m)	UX (m)	UY (m)	dx (m)	dy (m)	Delta (m)	H/delta
LIFT ROOM	7	0.018	0.151	0.001	0.010	0.010	727
L50	6	0.017	0.141	0.000	0.004	0.004	1493
L49	6.5	0.017	0.137	0.000	0.002	0.002	3041
L48	4	0.016	0.135	0.000	-0.001	0.001	3041
L47	4	0.016	0.136	0.000	0.003	0.003	1327
L46	4	0.016	0.133	0.000	0.003	0.003	1327
L45	4	0.015	0.130	0.000	0.003	0.003	1327
L44	4	0.015	0.127	0.000	0.003	0.003	1280
L43	4	0.015	0.124	0.000	0.003	0.003	1284
L42	4	0.014	0.121	0.000	0.003	0.003	1280
L41	4	0.014	0.118	0.000	0.003	0.003	1245
L40	4	0.014	0.115	0.000	0.003	0.003	1203
L39	4	0.013	0.111	0.000	0.003	0.003	1203
L38	4	0.013	0.108	0.000	0.003	0.003	1203
L37	4	0.013	0.105	0.000	0.003	0.003	1168
L36	4.3	0.012	0.101	0.001	0.003	0.003	1288
L35	4	0.012	0.098	0.000	0.003	0.003	1203
L34	4	0.011	0.095	0.001	0.003	0.003	1198
L33	4	0.011	0.092	0.000	0.004	0.004	1131
L32	4	0.010	0.088	0.000	0.004	0.004	1104
L31	4	0.010	0.084	0.001	0.003	0.003	1457
L30	4	0.009	0.082	0.000	0.003	0.003	1414
L29	4	0.009	0.079	0.001	0.004	0.004	1071
L28	4	0.008	0.075	0.000	0.004	0.004	1071
L27	4	0.008	0.072	0.001	0.004	0.004	1071
L26	4	0.007	0.068	0.001	0.004	0.004	1071
L25	4	0.007	0.064	0.001	0.004	0.004	1071
L24	4	0.006	0.060	0.001	0.004	0.004	1067
L23	4	0.006	0.057	0.001	0.004	0.004	1071
L22	4	0.005	0.053	0.001	0.004	0.004	1071
L21	4	0.005	0.049	0.000	0.003	0.003	1322
L20	4	0.004	0.046	0.001	0.003	0.003	1315
L19	4.3	0.004	0.043	0.001	0.004	0.004	1067
L18	4	0.003	0.039	0.001	0.004	0.004	1101
L17	4	0.003	0.036	0.001	0.004	0.004	1131
L16	4	0.002	0.032	0.000	0.004	0.004	1135
L15	4	0.002	0.029	0.000	0.003	0.003	1203
L14	4	0.002	0.025	0.000	0.003	0.003	1207
L13	4	0.001	0.022	0.000	0.003	0.003	1327
L12	4.9	0.001	0.019	0.000	0.004	0.004	1398
L11	4.9	0.001	0.016	-0.002	0.002	0.003	1666
L10	3.4	0.003	0.014	-0.001	0.002	0.002	2150
L9	3	0.004	0.012	0.001	0.002	0.002	1693
L8	3	0.003	0.011	0.001	0.002	0.002	1790
L7	3	0.003	0.009	0.000	0.002	0.002	1932
L6	3	0.002	0.008	0.000	0.002	0.002	1932
L5	3	0.002	0.006	0.000	0.001	0.001	2206
L4	3	0.002	0.005	0.001	0.001	0.001	2308
L3	5.1	0.001	0.004	0.001	0.002	0.002	2730
L2	4.5	0.001	0.002	0.000	0.001	0.001	4310
L1	4.5	0.000	0.001	0.000	0.001	0.001	7115
BASEMENT1	3.2	0.000	0.000	0.000	0.000	0.000	16000

APPENDIX F

ACCELERATION

Original Case

Height, H	212.600	m
Width, W	66.424	m
Depth, D	35.225	m
Period (mode 1)	6.121	s
Estimated fundamental natural frequency	0.163	Hz
Estimated critical damping ratio	0.050	
Mean wind speed at top building	15.000	m/s
Estimated maximum deflection at top building	0.219	m
Estimated average building density	185.000	kg/m^3
1. Gust Factor		
Roughness factor, r	0.290	
Aspect ratio W/H	0.312	
Background turbulence factor, B	0.470	
Reduced frequency	2.315	
Size reduction factor, S	0.020	
Inverse wavelenth	0.011	
Gust energy ratio, F	0.185	
Resonant turbulence factor, R	0.074	(R< B, hence resonant effects are small)
Average fluctuation rate, v	0.060	
Peak factor, gp	3.450	
Gust factor, G	1.738	
2. Along-wind acceleration	0.036	m/s^2
3. Cross-wind acceleration	0.007	m/s^2

Case 1 (CS1)

Height, H	212.600	m
Width, W	66.424	m
Depth, D	35.225	m
Period (mode 1)	6.674	s
Estimated fundamental natural frequency	0.150	Hz
Estimated critical damping ratio	0.050	
Mean wind speed at top building	15.000	m/s
Estimated maximum deflection at top building	0.217	m
Estimated average building density	185.000	kg/m^3
1. Gust Factor		
Roughness factor, r	0.290	
Aspect ratio W/H	0.312	
Background turbulence factor, B	0.470	
Reduced frequency	2.124	
Size reduction factor, S	0.025	
Inverse wavelenth	0.010	
Gust energy ratio, F	0.190	
Resonant turbulence factor, R	0.095	(R< B, hence resonant effects are small)
Average fluctuation rate, v	0.061	
Peak factor, gp	3.460	
Gust factor, G	1.754	
2. Along-wind acceleration	0.034	m/s^2
3. Cross-wind acceleration	0.008	m/s^2

Case 2 (CS2)

Height, H	212.600	m
Width, W	66.424	m
Depth, D	35.225	m
Period (mode 1)	6.785	s
Estimated fundamental natural frequency	0.147	Hz
Estimated critical damping ratio	0.050	
Mean wind speed at top building	15.000	m/s
Estimated maximum deflection at top building	0.206	m
Estimated average building density	185.000	kg/m^3
1. Gust Factor		
Roughness factor, r	0.290	
Aspect ratio W/H	0.312	
Background turbulence factor, B	0.470	
Reduced frequency	2.089	
Size reduction factor, S	0.026	
Inverse wavelenth	0.010	
Gust energy ratio, F	0.195	
Resonant turbulence factor, R	0.101	(R< B, hence resonant effects are small)
Average fluctuation rate, v	0.062	
Peak factor, gp	3.470	
Gust factor, G	1.761	
2. Along-wind acceleration	0.032	m/s^2
3. Cross-wind acceleration	0.008	m/s^2

Case 3 (CS3)

Height, H	212.600	m
Width, W	66.424	m
Depth, D	35.225	m
Period (mode 1)	5.761	s
Estimated fundamental natural frequency	0.174	Hz
Estimated critical damping ratio	0.050	
Mean wind speed at top building	15.000	m/s
Estimated maximum deflection at top building	0.190	m
Estimated average building density	185.000	kg/m^3
1. Gust Factor		
Roughness factor, r	0.290	
Aspect ratio W/H	0.312	
Background turbulence factor, B	0.470	
Reduced frequency	2.460	
Size reduction factor, S	0.023	
Inverse wavelenth	0.012	
Gust energy ratio, F	0.185	
Resonant turbulence factor, R	0.083	(R< B, hence resonant effects are small)
Average fluctuation rate, v	0.067	
Peak factor, gp	3.500	
Gust factor, G	1.755	
2. Along-wind acceleration	0.038	m/s^2
3. Cross-wind acceleration	0.007	m/s^2

Case 4 (CS4)

Height, H	212.600	m
Width, W	66.424	m
Depth, D	35.225	m
Period (mode 1)	7.097	s
Estimated fundamental natural frequency	0.141	Hz
Estimated critical damping ratio	0.050	
Mean wind speed at top building	15.000	m/s
Estimated maximum deflection at top building	0.152	m
Estimated average building density	185.000	kg/m^3
1. Gust Factor		
Roughness factor, r	0.290	
Aspect ratio W/H	0.312	
Background turbulence factor, B	0.470	
Reduced frequency	1.997	
Size reduction factor, S	0.029	
Inverse wavelenth	0.009	
Gust energy ratio, F	0.200	
Resonant turbulence factor, R	0.116	(R< B, hence resonant effects are small)
Average fluctuation rate, v	0.063	
Peak factor, gp	3.480	
Gust factor, G	1.773	
2. Along-wind acceleration	0.023	m/s^2
3. Cross-wind acceleration	0.009	m/s^2

APPENDIX G

MOMENT OF INERTIA OF STRUCTURES

Original Case (Walls)

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW1	W1	0.500	9.500	4.750	1.450	45.711
	W2	0.500	9.500	4.750	1.450	45.711
	W3	2.800	0.500	1.400	5.950	49.593
	W4	2.800	0.200	0.560	2.900	4.711
	W5	2.800	0.200	0.560	0.000	0.002
	W6	2.800	0.500	1.400	3.050	13.053
					Total	158.780

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW2	W7	0.500	9.500	4.750	1.450	45.711
	W8	0.500	12.400	6.200	0.000	79.443
	W9	0.500	12.400	6.200	0.000	79.443
	W10	2.800	0.500	1.400	5.950	49.593
	W11	2.800	0.200	0.560	2.900	4.711
	W12	2.800	0.200	0.560	0.000	0.002
	W13	2.800	0.500	1.400	3.050	13.053
	W14	2.700	0.500	1.350	5.950	47.822
	W15	2.700	0.200	0.540	2.900	4.543
	W16	2.700	0.200	0.540	0.000	0.002
	W17	2.700	0.200	0.540	2.900	4.543
	W18	2.700	0.500	1.350	5.950	47.822
					Total	376.686

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW3	W19	0.500	12.400	6.200	0.000	79.443
	W20	0.500	12.400	6.200	0.000	79.443
	W21	0.300	4.910	1.473	3.745	23.618
	W22	2.700	0.500	1.350	5.950	47.822
	W23	2.700	0.200	0.540	2.900	4.543
	W24	2.700	0.200	0.540	0.000	0.002
	W25	2.700	0.200	0.540	2.900	4.543
	W26	2.700	0.500	1.350	5.950	47.822
	W27	2.950	0.500	1.475	5.950	52.249
	W28	0.500	5.798	2.899	3.302	39.730
	W29	2.750	0.500	1.375	5.951	48.723
	W30	2.750	0.200	0.550	3.302	5.999
	W31	2.750	0.500	1.375	0.652	0.613
					Total	339.484

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW4	W32	0.500	3.900	1.950	4.250	37.694
	W33	0.500	3.900	1.950	4.250	37.694
	W34	2.900	0.500	1.450	2.550	9.459
	W35	2.900	0.500	1.450	5.950	51.364
					Total	136.210

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW5	W36	0.500	3.900	1.950	2.830	18.089
	W37	0.500	3.900	1.950	2.832	18.111
	W38	2.900	0.500	1.450	4.532	29.812
	W39	2.900	0.500	1.450	1.132	1.888
					Total	18.089

*Note

[Y] Distance from the centroid of walls to the reference point about X-axis

Case 1 (Walls)

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW1	W1	0.500	9.500	4.750	0.000	35.724
	W2	0.500	9.500	4.750	0.000	35.724
	W3	2.800	0.500	1.400	4.500	28.379
	W4	2.800	0.200	0.560	1.450	1.179
	W5	2.800	0.200	0.560	1.450	1.179
	W6	2.800	0.500	1.400	4.500	28.379
					Total	130.565

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW2	W7	0.500	9.500	4.750	0.000	35.724
	W8	0.500	12.400	6.200	1.450	92.478
	W9	0.500	12.400	6.200	1.450	92.478
	W10	2.800	0.500	1.400	4.500	28.379
	W11	2.800	0.200	0.560	1.450	1.179
	W12	2.800	0.200	0.560	1.450	1.179
	W13	2.800	0.500	1.400	4.500	28.379
	W14	2.700	0.500	1.350	4.500	27.366
	W15	2.700	0.200	0.540	1.450	1.137
	W16	2.700	0.200	0.540	1.450	1.137
	W17	2.700	0.200	0.540	4.350	10.220
	W18	2.700	0.500	1.350	7.400	73.954
					Total	393.611

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW3	W19	0.500	12.400	6.200	0.743	82.865
	W20	0.500	12.400	6.200	0.743	82.865
	W21	0.300	4.910	1.473	3.002	16.234
	W22	2.700	0.500	1.350	6.693	60.503
	W23	2.700	0.200	0.540	3.643	7.168
	W24	2.700	0.200	0.540	0.743	0.300
	W25	2.700	0.200	0.540	2.157	2.514
	W26	2.700	0.500	1.350	5.207	36.630
	W27	2.950	0.500	1.475	5.207	40.022
	W28	0.500	5.798	2.899	4.045	55.555
	W29	2.750	0.500	1.375	6.694	61.642
	W30	2.750	0.200	0.550	4.045	9.001
	W31	2.750	0.500	1.375	1.395	2.704
					Total	329.103

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW4	W32	0.500	3.900	1.950	3.507	26.455
	W33	0.500	3.900	1.950	3.507	26.455
	W34	2.900	0.500	1.450	1.807	4.765
	W35	2.900	0.500	1.450	5.207	39.344
					Total	97.018

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW5	W36	0.500	3.900	1.950	3.573	27.366
	W37	0.500	3.900	1.950	3.575	27.394
	W38	2.900	0.500	1.450	5.276	40.393
	W39	2.900	0.500	1.450	1.876	5.133
					Total	27.366

*Note

[Y] Distance from the centroid of walls to the reference point about X-axis

Case 2 (Walls)

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW1	W1	0.500	9.500	4.750	11.462	659.767
	W2	0.500	9.500	4.750	11.462	659.767
	W3	2.800	0.500	1.400	15.962	356.729
	W4	2.800	0.200	0.560	12.912	93.365
	W5	2.800	0.200	0.560	10.012	56.136
	W6	2.800	0.500	1.400	6.962	67.886
					Total	1893.650

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW2	W7	0.500	9.500	4.750	11.462	659.767
	W8	0.500	12.400	6.200	10.012	700.932
	W9	0.500	12.400	6.200	10.012	700.932
	W10	2.800	0.500	1.400	15.962	356.729
	W11	2.800	0.200	0.560	12.912	93.365
	W12	2.800	0.200	0.560	10.012	56.136
	W13	2.800	0.500	1.400	6.962	67.886
	W14	2.700	0.500	1.350	15.962	343.988
	W15	2.700	0.200	0.540	12.912	90.030
	W16	2.700	0.200	0.540	10.012	54.131
	W17	2.700	0.200	0.540	7.112	27.315
	W18	2.700	0.500	1.350	4.062	22.303
					Total	3173.515

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW3	W19	0.500	12.400	6.200	9.862	682.449
	W20	0.500	12.400	6.200	9.862	682.449
	W21	0.300	4.910	1.473	13.607	275.686
	W22	2.700	0.500	1.350	3.912	20.688
	W23	2.700	0.200	0.540	6.962	26.175
	W24	2.700	0.200	0.540	9.862	52.522
	W25	2.700	0.200	0.540	12.762	87.951
	W26	2.700	0.500	1.350	15.812	337.554
	W27	2.950	0.500	1.475	15.812	368.809
	W28	0.500	5.798	2.899	6.560	132.876
	W29	2.750	0.500	1.375	3.911	21.061
	W30	2.750	0.200	0.550	6.560	23.670
	W31	2.750	0.500	1.375	9.210	116.662
					Total	2534.283

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW4	W32	0.500	3.900	1.950	14.112	390.811
	W33	0.500	3.900	1.950	14.112	390.811
	W34	2.900	0.500	1.450	12.412	223.414
	W35	2.900	0.500	1.450	15.812	362.558
					Total	1367.595

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW5	W36	0.500	3.900	1.950	7.032	98.897
	W37	0.500	3.900	1.950	7.029	98.815
	W38	2.900	0.500	1.450	5.329	41.208
	W39	2.900	0.500	1.450	8.729	110.514
					Total	98.897

*Note

[Y] Distance from the centroid of walls to the reference point about X-axis

Case 3 (Walls)

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW1	W1	0.500	9.500	4.750	9.930	504.097
	W2	0.500	9.500	4.750	9.930	504.097
	W3	2.800	0.500	1.400	14.430	291.544
	W4	2.800	0.200	0.560	11.380	72.524
	W5	2.800	0.200	0.560	8.480	40.272
	W6	2.800	0.500	1.400	5.430	41.308
					Total	1453.843

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW2	W7	0.500	9.500	4.750	9.880	499.392
	W8	0.500	12.400	6.200	8.480	525.287
	W9	0.500	12.400	6.200	8.480	525.287
	W10	2.800	0.500	1.400	14.430	291.544
	W11	2.800	0.500	1.400	11.380	181.335
	W12	2.800	0.500	1.400	8.480	100.704
	W13	2.800	0.500	1.400	5.330	39.802
	W14	2.700	0.500	1.350	14.430	281.132
	W15	2.700	0.200	0.540	11.380	69.934
	W16	2.700	0.200	0.540	8.480	38.833
	W17	2.700	0.200	0.540	5.580	16.815
	W18	2.700	0.500	1.350	2.530	8.669
					Total	2578.735

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW3	W19	0.500	12.400	6.200	6.533	344.059
	W20	0.500	12.400	6.200	3.333	148.318
	W21	0.300	4.910	1.473	4.735	35.984
	W22	2.700	0.500	1.350	14.430	281.132
	W23	2.700	0.200	0.540	11.380	69.934
	W24	2.700	0.200	0.540	8.480	38.833
	W25	2.700	0.200	0.540	5.580	16.815
	W26	2.700	0.500	1.350	2.530	8.669
	W27	2.950	0.500	1.475	2.530	9.472
	W28	5.798	0.500	2.899	0.000	0.060
	W29	0.500	2.750	1.375	1.708	4.878
	W30	0.200	2.750	0.550	1.708	1.951
	W31	0.500	2.750	1.375	1.708	4.878
					Total	953.217

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW4	W32	0.500	3.900	1.950	4.230	37.363
	W33	0.500	3.900	1.950	4.230	37.363
	W34	2.900	0.500	1.450	5.930	51.019
	W35	2.900	0.500	1.450	2.530	9.312
					Total	135.056

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW5	W36	0.500	3.900	1.950	11.313	252.040
	W37	3.900	0.500	1.950	2.567	12.890
	W38	0.500	2.900	1.450	4.267	27.417
	W39	0.500	2.900	1.450	4.267	27.417
					Total	252.040

*Note

[Y] Distance from the centroid of walls to the reference point about X-axis

Case 4 (Walls)

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW1	W1	0.500	9.500	4.750	6.711	249.652
	W2	0.500	9.500	4.750	6.711	249.652
	W3	2.800	0.500	1.400	11.211	175.990
	W4	2.800	0.200	0.560	8.161	37.299
	W5	2.800	0.200	0.560	5.261	15.502
	W6	2.800	0.500	1.400	2.211	6.873
					Total	734.968

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW2	W7	0.500	9.500	4.750	6.661	246.476
	W8	0.500	12.400	6.200	5.261	251.047
	W9	0.500	12.400	6.200	5.261	251.047
	W10	2.800	0.500	1.400	11.211	175.990
	W11	2.800	0.500	1.400	8.161	93.272
	W12	2.800	0.500	1.400	5.261	38.779
	W13	2.800	0.500	1.400	2.111	6.268
	W14	2.700	0.500	1.350	11.211	169.705
	W15	2.700	0.200	0.540	8.161	35.967
	W16	2.700	0.200	0.540	5.261	14.948
	W17	2.700	0.200	0.540	2.361	3.012
	W18	2.700	0.500	1.350	0.689	0.669
					Total	1287.180

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW3	W19	0.500	12.400	6.200	5.722	282.439
	W20	0.500	12.400	6.200	3.333	148.318
	W21	0.300	4.910	1.473	9.467	134.976
	W22	2.700	0.500	1.350	0.228	0.098
	W23	2.700	0.200	0.540	2.822	4.302
	W24	2.700	0.200	0.540	5.722	17.682
	W25	2.700	0.200	0.540	8.622	40.145
	W26	2.700	0.500	1.350	11.672	183.946
	W27	2.950	0.500	1.475	11.672	200.978
					Total	1012.884

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW4	W32	0.500	3.900	1.950	9.972	196.381
	W33	0.500	3.900	1.950	9.972	196.381
	W34	2.900	0.500	1.450	8.272	99.248
	W35	2.900	0.500	1.450	11.672	197.572
					Total	689.582

Labeling		Length, b (m)	Width, d (m)	Area, A (m^2)	Y	Ixx (m^4)
LCW5	W36	0.500	3.900	1.950	2.889	18.747
					Total	18.747

*Note

[Y] Distance from the centroid of walls to the reference point about X-axis

Original Case (Columns)

Column	Radius (m)	Area (m^2)	Centroid Distance, Y	Ixx (m^4)
1	0.7	1.54	4.50	31.36
2	0.7	1.54	11.46	202.37
3	0.7	1.54	14.68	331.89
4	0.7	1.54	16.05	396.64
5	0.7	1.54	16.05	396.64
6	0.7	1.54	14.68	331.89
7	0.7	1.54	11.46	202.37
8	0.7	1.54	4.50	31.36
9	0.7	1.54	4.50	31.36
10	0.7	1.54	11.46	202.37
11	0.7	1.54	14.68	331.89
12	0.7	1.54	16.05	396.64
13	0.7	1.54	16.05	396.64
14	0.7	1.54	14.68	331.89
15	0.7	1.54	11.46	202.37
16	0.7	1.54	4.50	31.36
17	0.875	2.40	0.00	0.46
18	0.875	2.40	0.00	0.46
			Total	3849.921

Case 1 (Columns)

Column	Radius (m)	Area (m^2)	Centroid Distance, Y	Ixx (m^4)
1	0.7	1.54	11.46	202.37
2	0.7	1.54	14.68	331.89
3	0.7	1.54	16.05	396.64
4	0.7	1.54	16.05	396.64
5	0.7	1.54	14.68	331.89
6	0.7	1.54	11.46	202.37
7	0.7	1.54	11.46	202.37
8	0.7	1.54	14.68	331.89
9	0.7	1.54	16.05	396.64
10	0.7	1.54	16.05	396.64
11	0.7	1.54	14.68	331.89
12	0.7	1.54	11.46	202.37
13	0.875	2.40	0.00	0.46
14	0.875	2.40	0.00	0.46
15	0.7	1.54	5.48	46.34
16	0.7	1.54	5.48	46.34
17	0.7	1.54	5.48	46.34
18	0.7	1.54	5.48	46.34
			Total	3909.867

*Note

[Y] Distance from the centroid of columns to the reference point about X-axis

Case 2 (Columns)

Column	Radius (m)	Area (m^2)	Centroid Distance, Y	Ixx (m^4)
1	0.7	1.54	4.50	31.36
2	0.7	1.54	11.46	202.37
3	0.7	1.54	14.68	331.89
4	0.7	1.54	14.68	331.89
5	0.7	1.54	11.46	202.37
6	0.7	1.54	4.50	31.36
7	0.7	1.54	4.50	31.36
8	0.7	1.54	11.46	202.37
9	0.7	1.54	14.68	331.89
10	0.7	1.54	14.68	331.89
11	0.7	1.54	11.46	202.37
12	0.7	1.54	4.50	31.36
13	0.875	2.40	0.00	0.46
14	0.875	2.40	0.00	0.46
15	0.7	1.54	4.50	31.36
16	0.7	1.54	4.50	31.36
17	0.7	1.54	4.50	31.36
18	0.7	1.54	4.50	31.36
			Total	2388.798

Case 3 (Columns)

Column	Radius (m)	Area (m^2)	Centroid Distance, Y	Ixx (m^4)
1	0.7	1.54	4.50	31.36
2	0.7	1.54	11.46	202.37
3	0.7	1.54	14.68	331.89
4	0.7	1.54	16.05	396.64
5	0.7	1.54	16.05	396.64
6	0.7	1.54	14.68	331.89
7	0.7	1.54	11.46	202.37
8	0.7	1.54	4.50	31.36
9	0.7	1.54	4.50	31.36
10	0.7	1.54	11.46	202.37
11	0.7	1.54	11.46	202.37
12	0.7	1.54	4.50	31.36
13	0.875	2.40	0.00	0.46
14	0.875	2.40	0.00	0.46
15	0.7	1.54	4.50	31.36
16	0.7	1.54	6.20	59.35
17	0.7	1.54	6.20	59.35
18	0.7	1.54	4.50	31.36
			Total	2574.295

*Note

[Y] Distance from the centroid of columns to the reference point about X-axis

Case 4 (Columns)

Column	Radius (m)	Area (m^2)	Centroid Distance, Y	Ixx (m^4)
1	0.7	1.54	4.5	31.36
2	0.7	1.54	14.68	331.89
3	0.7	1.54	16.05	396.64
4	0.7	1.54	16.05	396.64
5	0.7	1.54	14.68	331.89
6	0.7	1.54	11.46	202.37
7	0.7	1.54	4.50	31.36
8	0.7	1.54	4.50	31.36
9	0.7	1.54	11.46	202.37
10	0.7	1.54	14.68	331.89
11	0.7	1.54	16.05	396.64
12	0.7	1.54	16.05	396.64
13	0.7	1.54	14.68	331.89
14	0.7	1.54	4.50	31.36
15	0.7	1.54	4.50	31.36
16	0.7	1.54	4.50	31.36
17	0.875	2.40	4.50	49.16
18	0.875	2.40	4.50	49.16
			Total	3605.301

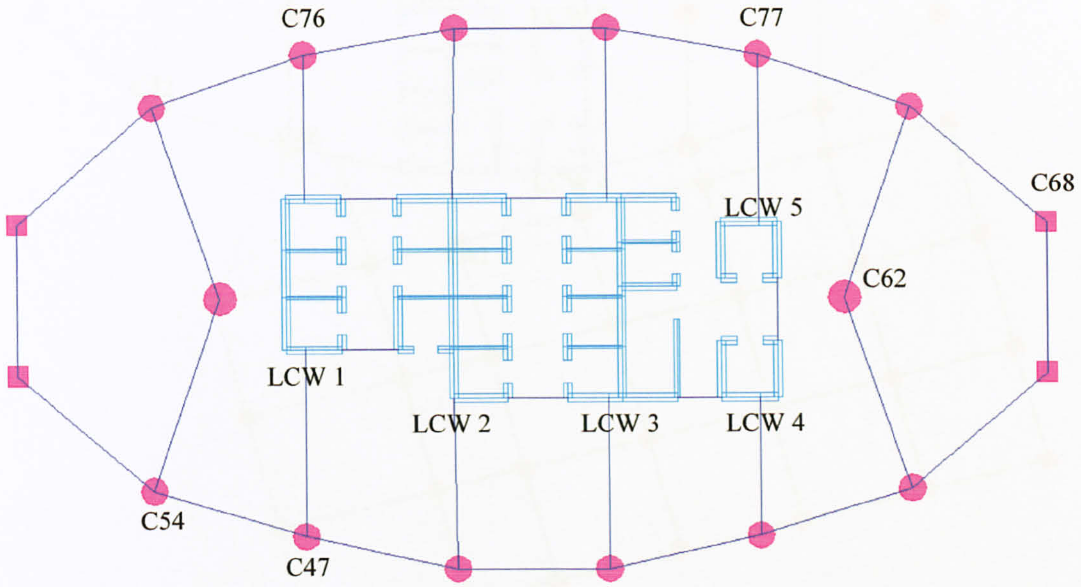
*Note

[Y] Distance from the centroid of columns to the reference point about X-axis

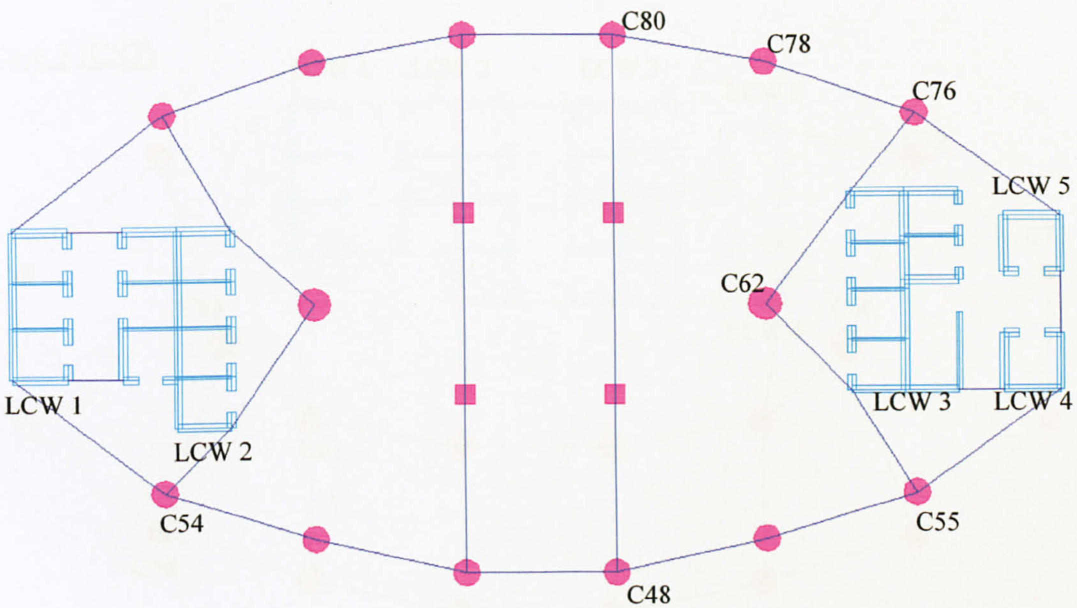
APPENDIX H

LOCATION OF COLUMNS & WALLS CORRESPONDING TO MAXIMUM FORCES

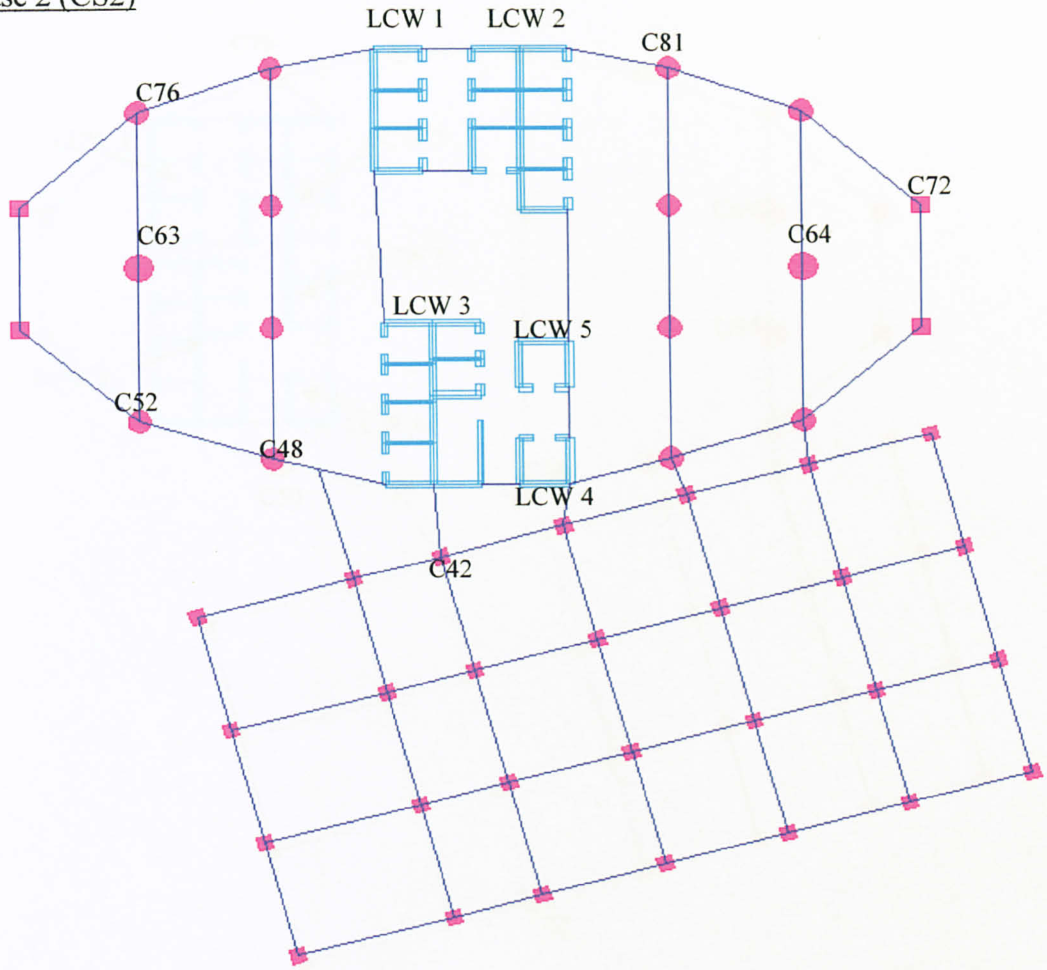
Original Case



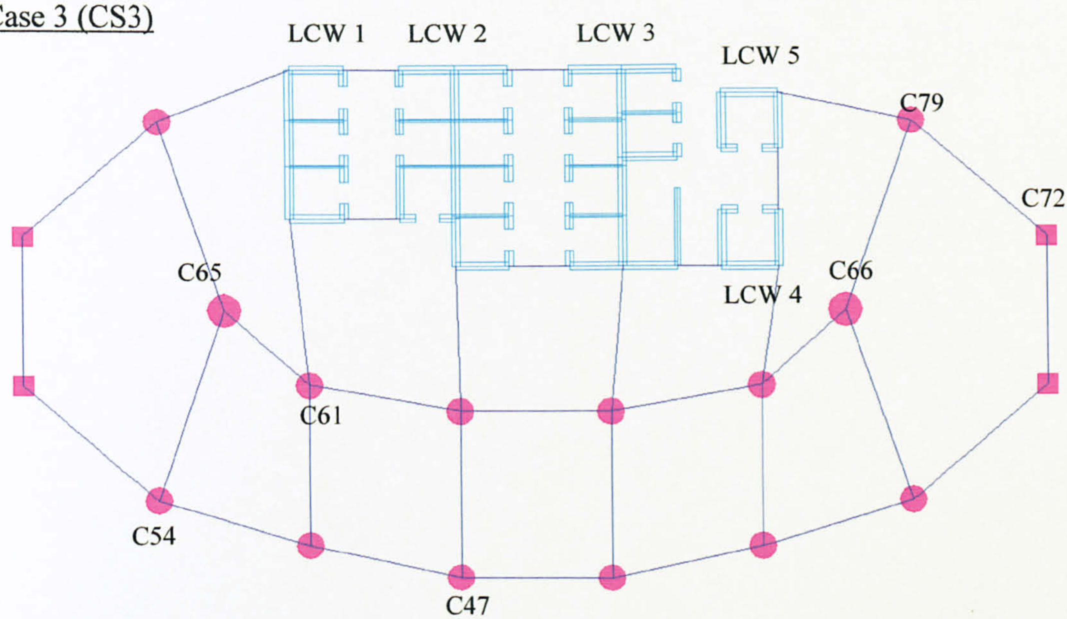
Case 1 (CS1)



Case 2 (CS2)



Case 3 (CS3)



Case 4 (CS4)